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Hydrogeology of Parts of the Twin Platte and Middle Republican Natural Resources Districts, Southwestern Nebraska

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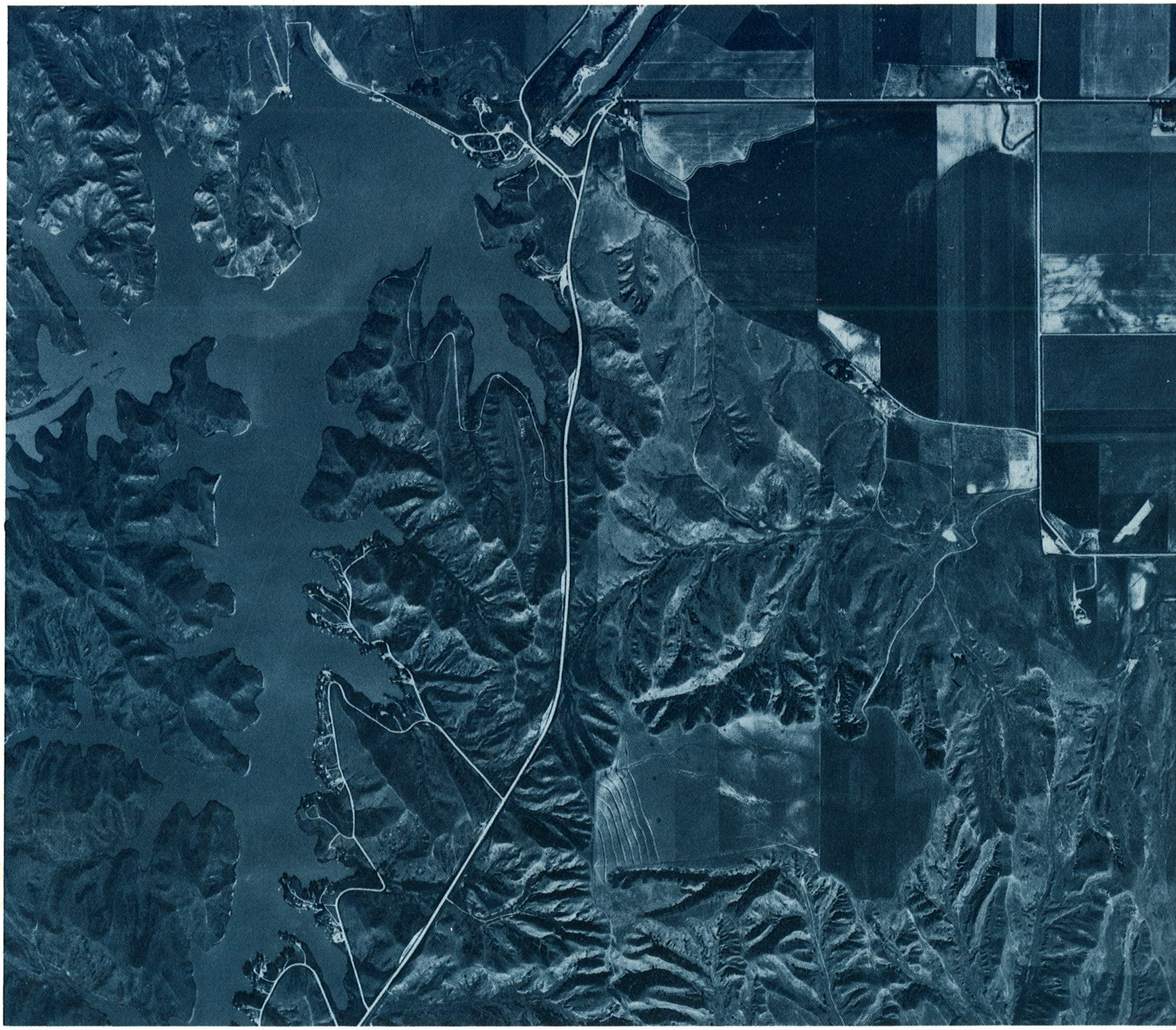

Nebraska Water Survey Paper No. 70

Prepared in Cooperation with the U.S. Geological Survey

Conservation and Survey Division
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln

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Cover photo:
Jeffrey Reservoir, left, and Tri-County Supply Canal, top middle, in Lincoln County. Jeffrey Hydroelectric Plant sits by the dam's outlet.

April 1992

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Factors for Converting U.S. Customary Units to International System (SI) Units

Multiply	By	To Obtain
acre	0.0040	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per mile (acre-ft/mi)	1,984	cubic meter per kilometer
inch (in.)	25.4	millimeter
inch per hour (in./hr)	25.4	millimeter per hour
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.18943	meter per kilometer
cubic foot (ft^3)	0.02832	cubic meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
mile (mi)	1.609	kilometer
degree Fahrenheit (°F)	C = 5/9 (°F - 32)	degree Celsius

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

Abstract

The hydrogeologic system in southwestern Nebraska, which has been affected by surface-water seepage and groundwater irrigation, has been described and simulated to evaluate quantitatively the effects of surface-water seepage and management practices on streamflows and groundwater levels.

Two surface-water projects, beginning in 1936 and 1940, diverted water through the study area using canals and reservoirs located on the south side of the Platte River system. Seepage of surface water from the canals and reservoirs caused mounding of the water table, with groundwater rises of 15 ft by 1980 south of the South Platte and Platte rivers in Lincoln County. The seepage and resulting rises in water levels altered the groundwater flow patterns. Three reservoirs, two in 1953 and one in 1962, were constructed along the Republican River and its tributaries. By 1980, seepage from the reservoirs had produced groundwater rises of 10 to 40 ft adjacent to the impoundments.

The quality of water in the aquifer, which consists of the Ogallala Group and Quaternary deposits, was evaluated by collecting and analyzing groundwater samples from 20 observation wells during 1977 and 1978 and from 99 irrigation wells during 1979. The specific conductances of the water samples increased approximately 40 percent in the uplands from west to east across the study area. The specific conductance of the water was larger in the Platte River and Republican River valleys than in the uplands. This probably was caused by mineralized water seeping from the rivers and canals. Groundwater was determined to be suitable for humans and irrigation uses throughout the study area.

Recoverable groundwater in storage within the study area during 1935 was estimated to have been 141 million acre-ft. During 1978 this figure had increased to 145 million acre-ft as a result of seepage from canals and reservoirs. Soil-zone and recharge-discharge models were used to estimate fluxes. These data were used in a finite-element groundwater flow model (RAQSIM) of the saturated zone. The groundwater flow model was calibrated for 1935 through 1978 by decreasing the differences between the measured and computed water levels and streamflows to acceptable levels. The groundwater flow model was used to simulate three management alternatives for the 3,970 mi^2 study area. A minimum development with no additional acres irrigated after 1980 was evaluated for groundwater-application rates of 6, 9, 12, 15, and 18 in. per year. A maximum development of a 10-percent increase in irrigated acreage and a moderate development of a 2.5-percent increase with the application rates above were also evaluated. By the year 2020, using the moderate development rate and a 12-in. application rate, the recoverable groundwater in storage would decrease by 11.3 percent from the 1980 amount; streamflow in Red Willow and Medicine creeks would decrease approximately 80 percent from the average simulated flow on September 1 and December 1, 1981. Also, with these development and application rates, water-level declines of 20 to 40 ft would occur over much of the study area by the year 2020.

Introduction

Diversion of surface water from the Platte River system and construction of reservoirs have altered the groundwater system in southwestern Nebraska (fig. 1). During 1936, the Nebraska Public Power District began diverting water for power generation from the North Platte River into the South Platte River valley through Sutherland Canal to Sutherland Reservoir, Lake Maloney, and back to the South Platte River south of North Platte. In 1940, the Central Nebraska Public Power and Irrigation District began diverting water from the Platte River east of the confluence of the North Platte and South Platte rivers into Tri-County Canal, which flows along the south side of the Platte River. This water is used for irrigation and power generation in south-central Nebraska.

Seepage of surface water from Sutherland Reservoir and Sutherland Canal has created mounds in the water table, blocking the natural groundwater movement into the South Platte Valley. By 1980, groundwater levels had risen 10 to 15 ft in an area that extended 30 mi across western Lincoln County and 15 to 20 mi to the south.

Seepage from the Tri-County Canal also created mounds in the water table south of the Platte River. This seepage has caused water-level rises of 10 to 60 ft in eastern Lincoln County.

By 1953, water was impounded by Trenton Dam on the Republican River in Hitchcock County and Medicine Creek Dam in Frontier County. In 1962, Red Willow Dam on Red Willow Creek began impounding water in southwestern Frontier County. By 1980, seepage from these impoundments had produced groundwater-level rises adjacent to the reservoirs of 10 to 40 ft.

Groundwater irrigation developed slowly through the 1950s; only 250 irrigation wells had been drilled in the uplands between the Platte and Republican rivers by 1960. By 1980, however, the number of irrigation wells had increased to more than 2,000 in the upland area, but resulting water-level declines were either absent or minor throughout the study area (fig. 2).

Possible future groundwater-level declines and the need for a method to evaluate water-resource alternatives resulted in a cooperative agreement between the Twin Platte and Middle Republican natural resources districts (NRDs), the Conservation and Survey Division (CSD) of the University of Nebraska–Lincoln, and the U.S. Geological Survey (USGS) to conduct a quantitative hydrogeologic study. The results of this study are to serve as a basis for evaluating the hydrogeology of the area and the effects of various management practices.

Purpose and Scope

This report presents the results of a study 1) to describe the hydrogeologic system; 2) to identify changes in that system from 1935 to 1978; and 3) to develop and demonstrate a capability for evaluating quantitatively the effects of management practices on seepage losses, streamflow, and groundwater levels.

The scope included the development of a groundwater flow model that uses new and existing data. Mathematical models of the different components of the hydrogeologic system—the surface-water system, soil zone, and saturated zone—were developed and used. Output from these models serve as input to the groundwater flow model of the saturated zone, which simulates the effects of changes in recharge and discharge on groundwater levels and streamflows. The surface-water system is included in the groundwater flow model only to the extent necessary to determine the effects of surface water on recharge to the aquifer or of groundwater discharge to the surface-water system. The unsaturated zone was not analyzed by mathematical programs. Water movement between the soil zone and the unsaturated zone was assumed to be direct and without losses.

New field data collected for this study include the following: 1) fifty-eight test holes drilled to a few feet below the base of the Ogallala Group or the oldest Quaternary deposits; 2) mass water-level measurements made in the spring of 1977 and 1978; 3) water from different levels within the aquifer that was sampled and analyzed at more than 100 different locations.

In addition to this report, a report has been published that documents the flow model used in this study and describes the support programs (Cady and Peckenpaugh, 1985). An unpublished paper that describes the geologic units within each of the 58 test holes has been prepared by the CSD.

Previous Studies

Although earlier investigators examined the groundwater resources of central and southwestern Nebraska, Waite and others (1946) were the first to publish a preliminary study on groundwater in the Republican River valley. The report contains information about saturated thickness in the Republican River valley and tributaries throughout Red Willow and Hitchcock counties, valley cross sections, bedrock contours from the Republican River valley south to Beaver and Driftwood Creek valleys, and logs of many shallow test holes drilled from 1933 to 1942.

C. R. Johnson (1960) described the groundwater resources in an area bounded by the Platte River on the north, the Republican River on the south, the Frenchman Creek drainage on the west and the Big Blue-Little Blue rivers drainage on the east. Although the data, collected from 1948 to 1952, were widely scattered in much of the western part of the area, total recharge was estimated to be approximately 1.2 million acre-ft per year. Johnson estimated that the number of irrigation wells with large discharges could be quadrupled before withdrawals would equal recharge

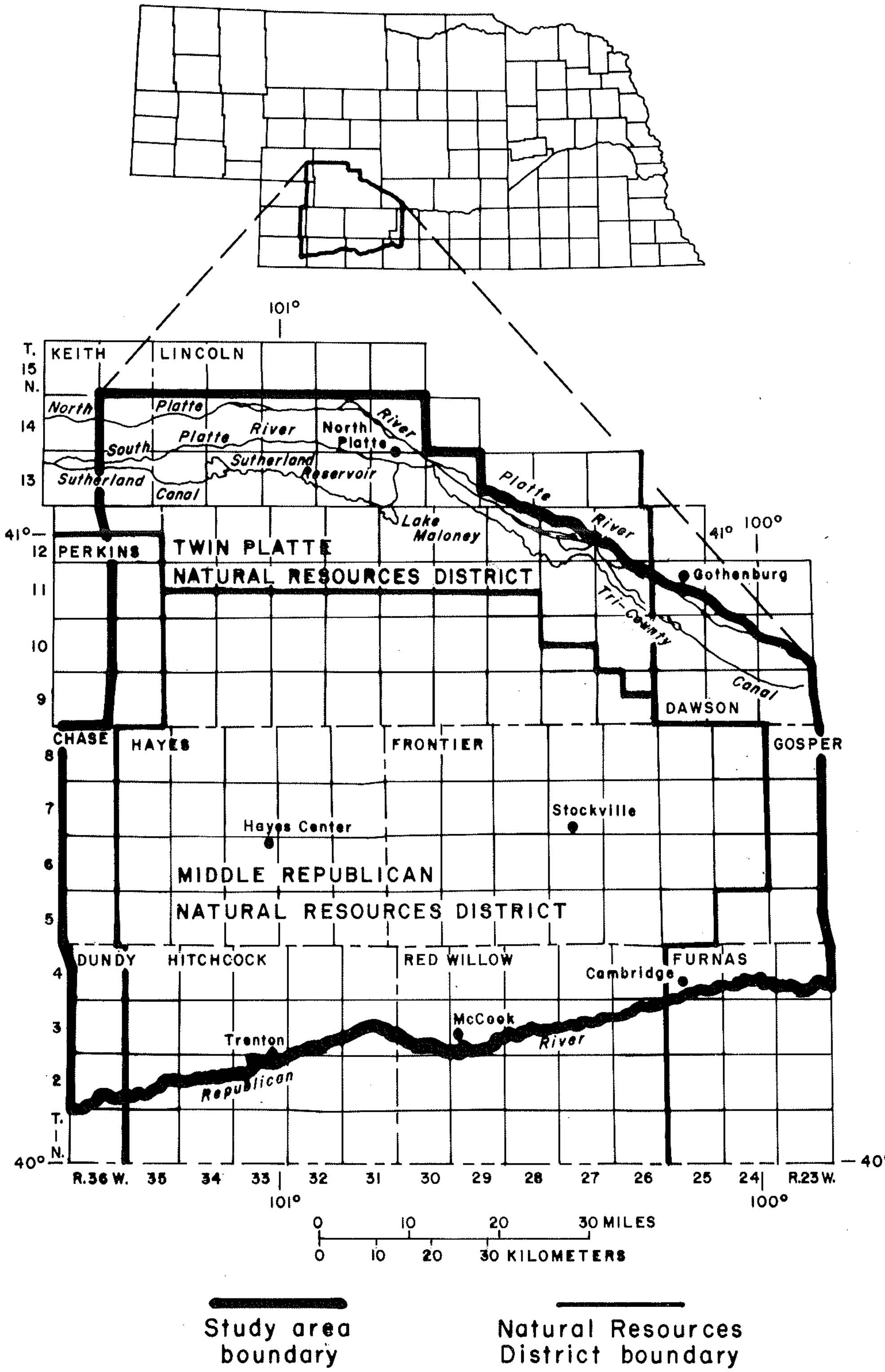


Fig. 1. Location of the study area.

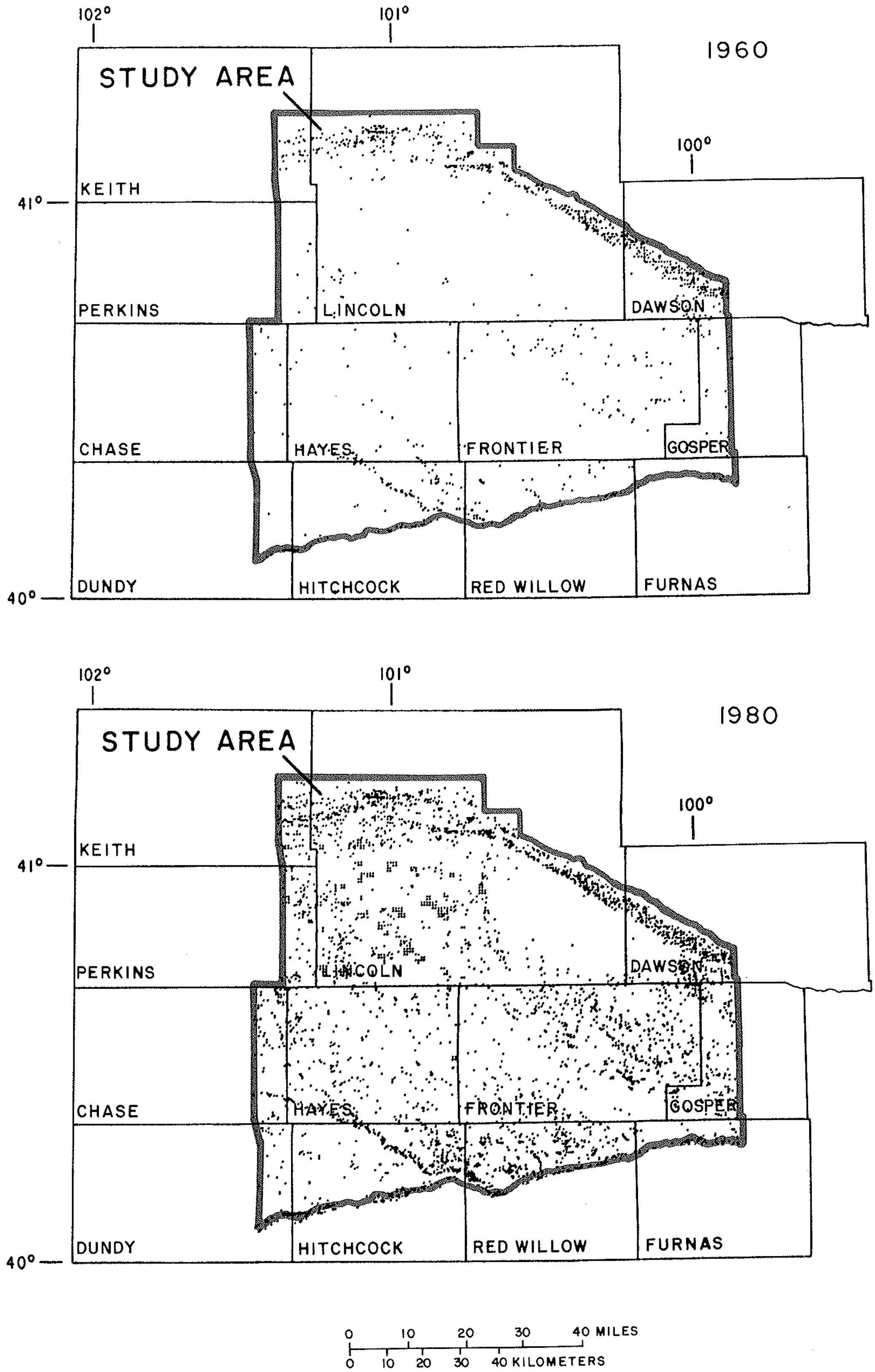


Fig. 2. Location of registered irrigation wells, 1960 and 1980.

but cautioned that large concentrations of irrigation wells could create water-table declines and streamflow capture in the areas where wells were concentrated.

Cardwell and Jenkins (1963) evaluated the groundwater resources in the Frenchman Creek basin, which adjoins the study area on the west. Their conclusions, based on data collected from 1951 to 1953 and conservative estimates of irrigation development in the future, indicated that groundwater discharge to Frenchman Creek virtually would cease by the year 2008. A reassessment of the work of Cardwell and Jenkins became necessary when extensive development of center-pivot irrigation systems in the basin during the 1960s and 1970s increased groundwater withdrawals. Leonard and Huntoon (1974) identified additional water-table declines and a lessening of the baseflow of Frenchman Creek.

Lappala (1976, 1978) studied and modeled the hydrogeologic system in Keith, Perkins, Chase, and Dundy counties between the South Platte and Republican rivers. Groundwater declines of as much as 19 ft from 1952 to 1975 were identified in central and western Chase County. A groundwater rise of as much as 13 ft from 1937 to 1967 in northern Perkins and southern Keith counties was identified and attributed to increased recharge resulting from the dryland farming practice of alternating years of producing wheat with fallow fields to conserve moisture. A groundwater model was developed as a tool for projecting future water levels under different irrigation developments. Model projections were made assuming minimum development (no additional development beyond 1975) and maximum development (continued development at the average rate that occurred during 1970-1975). The estimated 68 million acre-ft of groundwater in storage in 1975 would be decreased 2.8 percent by the year 2000 with minimum development and 3.7 percent with maximum development. It was also predicted that, if maximum development occurred, flow in Frenchman Creek near Imperial, Stinking Water Creek at the Chase-Hayes county line, and Spring Creek at the Chase-Hayes county line would be eliminated by 1992.

By 1978 the decreased flow of Frenchman Creek into Enders Reservoir resulted in a shortage of about 8,700 acre-ft of surface water scheduled for delivery to the Hitchcock-Red Willow,Frenchman Valley, and Meeker-Driftwood irrigation districts. Lappala and others (1978) evaluated the availability of groundwater in the irrigation districts that could offset the decreased surface-water deliveries. Two supply-well configurations, one along Frenchman Creek and the other in the uplands just north of McCook, were simulated and determined to be incapable of meeting the delivery shortages. Existing private irrigation wells on lands of U.S. Bureau of Reclamation projects were determined to be capable of providing all consumptive irrigation requirements for 19 yrs in the absence of surface-water supplies from Enders Reservoir. Water-level declines and streamflow depletions were estimated for each of the analyses.

Eversoll (1977) delineated bedrock outcrops, water-table configuration, and aquifer thickness in Red Willow County. Eversoll's work has been incorporated into the geologic mapping of the McCook 1:250,000-scale topographic map (Eversoll and others, 1988).

R. F. Diffendal, Jr. of CSD (University of Nebraska-Lincoln) has mapped the geology of the North Platte 1:250,000-scale topographic map. The map was published by the U.S. Geological Survey in 1991 in the miscellaneous investigations series as map no. I-2277.

Method of Investigation

The hydrogeologic system was divided for analysis into the following components: surface-water system, soil zones, unsaturated zone, and saturated zone. A finite-element groundwater flow model was developed and calibrated by using the hydrogeologic data and recharge-discharge data estimated from computer programs. The groundwater flow model was used to understand the hydrogeologic system and to assess the effects of irrigation development.

The geology of the study area was further defined by drilling 58 test holes. Soils were grouped according to existing county soil surveys. Climate, water-level fluctuations, streamflow, water use, and water quality were measured in the field or taken from available records.

The hydrogeologic system was simulated for three periods: 1) 1935 (assumed to be steady-state), before groundwater and surface-water development; 2) 1935 to 1978, during which surface-water diversions and irrigation development affected the system; and 3) 1980 to 2020, for future irrigation development.

System for Numbering Wells and Test Holes

Wells and test holes in this report have been assigned location numbers within the U.S. Bureau of Land Management system (fig. 3) that are on file at the CSD Lincoln office. The numeral preceding N in the location number indicates the township, the number preceding W indicates the range, and the number preceding the lower-case letters indicates the section. The lower-case letters denote, in order, the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section. These letters are assigned a counter-clockwise direction, beginning with the northeast division.

The other number identifying test holes is a field number, which consists of three parts, the first of which is a sequential number and the last the year drilled. The middle letter for those holes drilled in 1977 and 1978 indicates the contractor who did the drilling—either F for Feighny Drilling Company or H for Haggard Drilling Company. The middle letter for earlier test holes designates the type of drilling machine used.

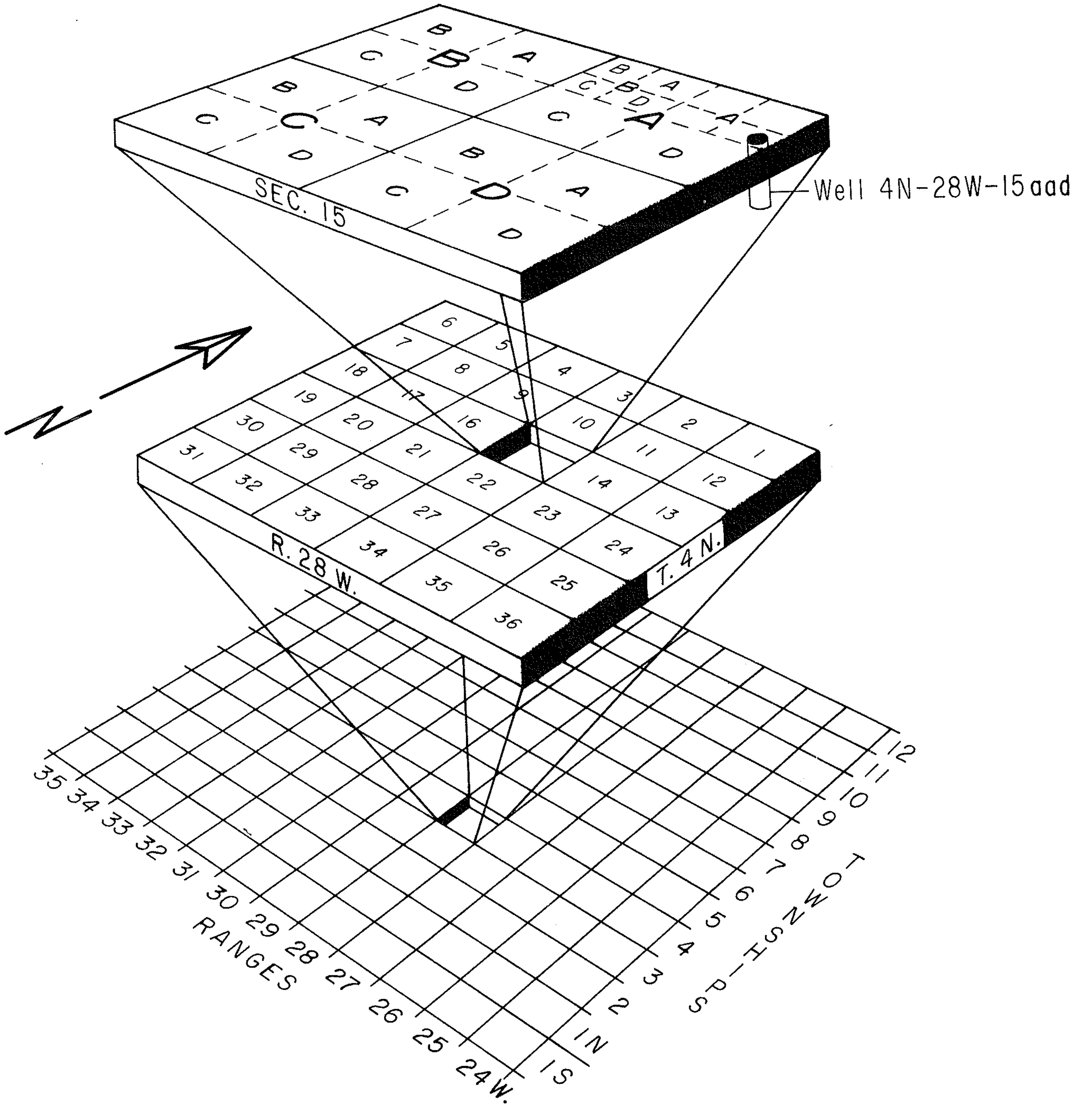


Fig. 3. Well and test-hole numbering system.

Acknowledgments

The authors express appreciation to the hundreds of landowners who so willingly cooperated in the test-hole drilling, water-level measuring, and water-quality sampling; the personnel of the Twin Platte and Middle Republican natural resources districts (NRDs) who assisted in these field efforts; and the personnel of the Nebraska Public Power District, the U.S. Bureau of Reclamation, and the Central Nebraska Public Power and Irrigation District, who provided essential data.

The authors also thank the following staff members of the Conservation and Survey Division: Ray Bentall for his work in developing the predevelopment water-table contour map and the water-level change maps, and for his careful review of other illustrations and text; Duane Eversoll and Robert F. Diffendal, Jr., for their work on the map showing the base of the aquifer; Vincent Dreeszen for his work on the transmissivity map; Dee Ebbeka and Jerry Leach for their cartographic expertise and patience; Audrey Schardt and Bernice Goemann for their typing skills; and Charles Flowerday for his editing and production expertise.

Physical Setting

The physical setting of the study area can be described by its physiography and drainage, geology, climate, soils, natural vegetation, and land use. These items have been important in developing the groundwater and surface-water resources of this area.

Location

The Twin Platte-Middle Republican study area is located in southwestern Nebraska (fig. 1). It is bounded on the north by the North Platte and Platte rivers and on the south by the Republican River. The original study area included all of Hayes and Frontier counties, the southern half of Lincoln County, and the northern part of Red Willow and Hitchcock counties. The northern 20 percent of the original study area was within the Twin Platte NRD, and the remaining 80 percent was within the Middle Republican NRD. The study area was extended to include all the area shown in figure 1 in order to better simulate the hydrogeologic system. This area includes the previously described original study area and parts of Keith, Perkins, Chase, and Dundy counties on the west and parts of Dawson, Gosper, and Furnas counties on the east.

Physiography and Drainage

The Twin Platte-Middle Republican area is located in the High Plains subsection of the Great Plains physiographic province (Fenneman, 1931). This subsection is typified by broad intervalley remnants of the Ogallala plain mantled by Pleistocene silts and Holocene sands. The South Platte and Platte rivers drain the northern part of the area. The Republican River and its primary tributaries—Frenchman Creek, Stinking Water Creek, Red Willow Creek, Blackwood Creek, and Medicine Creek—drain the central and southern parts of the area. The major surface-water impoundments are Sutherland Reservoir, Lake Maloney, and Jeffrey Reservoir in Lincoln County; Swanson Lake in Hitchcock County; and Hugh Butler and Harry Strunk lakes in Frontier County.

Reed (1969) divided the state into 13 "underground water" (groundwater) areas based on landforms, surface-water drainage, geology, and soils. The study area includes parts of five of these underground water areas (fig. 4) as follows:

The Platte River Valley Region consists of the flood plains and bordering terrace lands along the North Platte, South Platte, and Platte rivers. This area is underlain by Pleistocene sands and gravels and the Ogallala Group. Depths to water range from 0 to 40 ft, and the well yields are ample for irrigation.

In the northwestern corner of the study area is a narrow, much-dissected upland between the North Platte and South Platte rivers. This ridge is an eastward extension of the Southern Panhandle Tableland Region. No irrigation wells have been drilled on this upland remnant.

The Southwestern Tableland Region comprises most of southwestern Lincoln County. Broad southeast- and east-trending extensions of the tableland reach into Hayes and western Hitchcock counties. The land surface in this region has a slight eastward slope with low rolling relief. Surficial materials consist mostly of Pleistocene loess, which is mantled in southwestern Lincoln County and in parts of Hayes County by a veneer of sand. The entire region is underlain by the Ogallala Group, which ranges in thickness from 100 ft in the south to more than 500 ft in the north. Throughout this area the Ogallala is capable of providing ample water for irrigation.

The Republican River Valley and Dissected Plains Region comprise the rest of the study area except for a small part of the South Central Plains Region in the southeastern corner of Lincoln County. The valleys of the Republican River and Frenchman Creek, in contrast to the Platte Valley, are underlain by a relatively thin sequence of Pleistocene sands and gravels that overlie Cretaceous bedrock consisting of impermeable shale and chalk. Irrigation wells are numerous in the Republican River and Frenchman Creek valleys but are shallow and generally of minimal discharge.

The Dissected Plains Region has moderate relief where southeastward-flowing tributaries of the Republican River have eroded headward into the slightly sloping uplands. Steep-sided valleys and flat intervalley uplands characterize this part of the region. Topographic relief is greater, however, in southeastern Lincoln County, where north-flowing tributaries of the Platte River have cut steep-sided canyons sep-

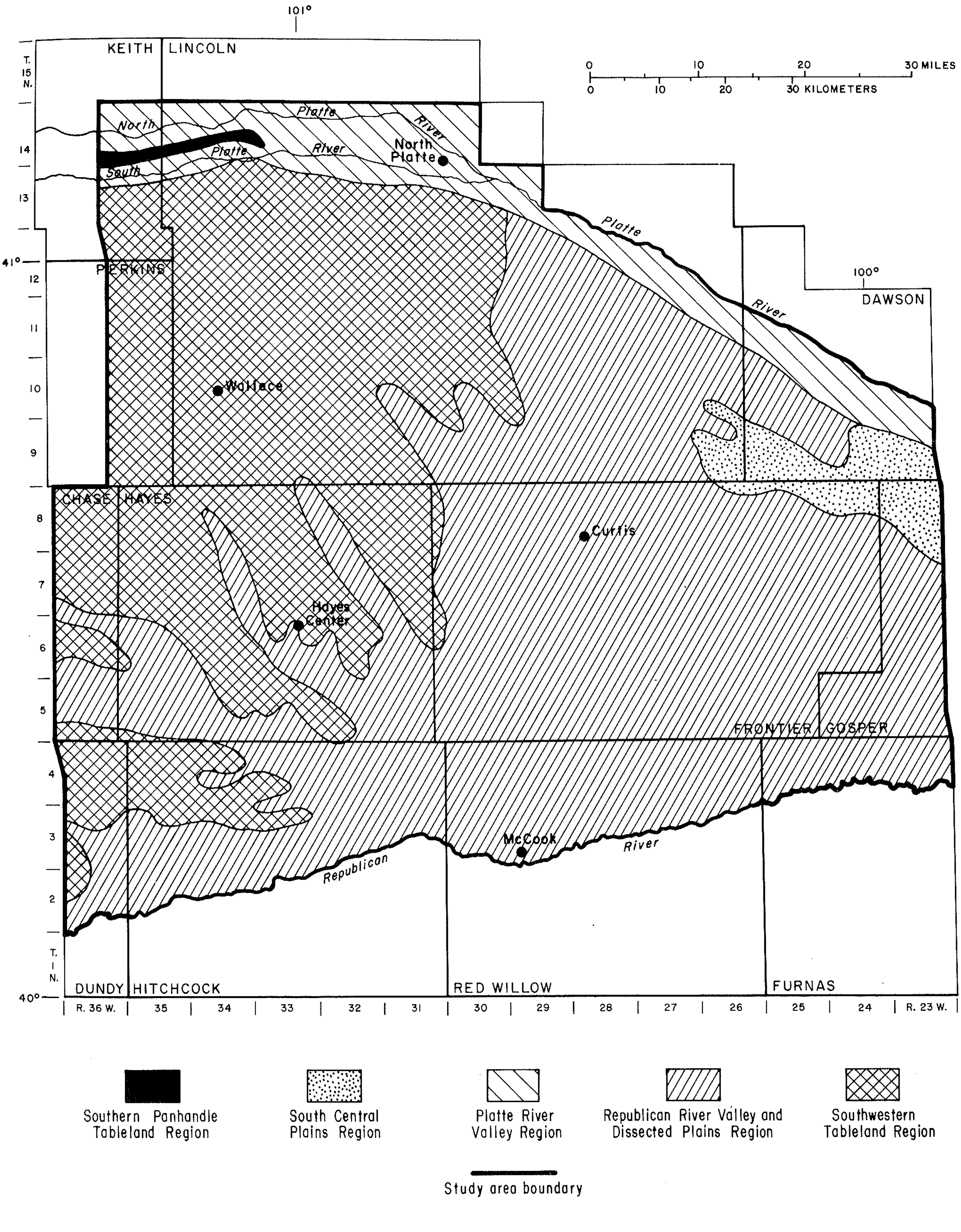


Fig. 4. Underground water (groundwater) areas.

arated by narrow ridges. The entire region is underlain by the Ogallala Group, which ranges from a few feet thick in the south to more than 400 ft in the north. Well yields differ greatly from place to place but generally are adequate for irrigation. The density of irrigation wells is less in this region than in the slightly rolling, less dissected Southwestern Tableland Region.

Geology

The water-bearing units in the Twin Platte-Middle Republican study area were deposited during the last 20 million yrs by streams flowing eastward from the Rocky Mountains. These units comprise the High Plains Aquifer, which consists mainly of one or more hydraulically connected geologic units of late Tertiary or Quaternary age (Gutentag and others, 1984). The Ogallala Group is the principal unit in the High Plains Aquifer within the study area. The geologic units considered significant in the area are summarized in table 1.

The oldest unit is the Niobrara Formation, a dark gray-green marine chalk deposited in Late Cretaceous time. Where penetrated by drilling, the upper surface of the Niobrara commonly is a weathered yellow or white chalk that grades to a dark, gray-green color. The Niobrara is not a significant source of water in the area. In the eastern part of the study area, where the Niobrara is overlain unconformably by the Ogallala Group, the base of the aquifer is the erosional surface cut into the Niobrara Formation. Uplift has caused erosion and removal of the overlying Pierre Shale, thus causing the Niobrara Formation to subcrop along a north-south band about 20 mi wide and centered on a line from Gothenburg to Cambridge (fig. 1). The Niobrara Formation ranges from about 50 ft to as much as 500 ft thick in the study area.

The erosional surface cut into the Pierre Shale is considered to be the base of the aquifer where the Pierre Shale is overlain by the Ogallala Group. The Pierre Shale is a black marine shale that ranges from 0 ft in eastern Frontier County to as much as 1,200 ft near the southwestern boundary of the study area. The sea in which the Pierre Shale was deposited began to withdraw approximately 65 million yrs ago at the end of the Cretaceous Period as the Rocky Mountain uplift began. For approximately 30 million yrs the exposed surface of the Niobrara Formation and Pierre Shale was eroded and weathered. The top of the Cretaceous units is recognized locally as a weathered yellow zone referred to as "ochre" by drillers and a paleosol (ancient soil) by geologists. In many places a hard, multi-hued chert or flint marks the top of the Cretaceous units.

Approximately 35 million yrs ago, the first fine-grained sediments from the Rocky Mountains were deposited on the weathered surface of the Pierre Shale. For about 7 million yrs, the clays, claystones, silts, and siltstones of the Chadron and Brule formations of the White River Group were deposited. Neither formation yields significant quantities of water in the study area and where present, their erosional surfaces form the base of the aquifer. Although undifferentiated for this study, the Chadron Formation varies in thickness from 0 ft to about 90 ft and the Brule Formation from 0 ft to about 120 ft.

Following deposition of the Chadron and Brule formations, the area was subject to erosion until about 18 million yrs ago, when, in response to renewed uplift in the Rocky Mountains, the eastward-flowing streams regained their energy and source of sediment. The valleys that were cut into the Niobrara-Pierre-White River bedrock were filled with sediments, and a broad aggrading plain was established. Streams meandered across this plain until approximately 6 million yrs ago and deposited a heterogeneous mass of clays, silts, sands, sandstones, and gravels referred to as the Ogallala Group. Much of the Ogallala Group is cemented by calcium carbonate. Outcrops of the Ogallala Group are common in the valleys extending from the Republican River valley into southern Hayes and Frontier counties. The Ogallala is the principal aquifer in the area and ranges from 0 ft along the north side of the Republican River valley to more than 500 ft in the Platte Valley east of North Platte. The locations of test holes that provided data on subsurface conditions are shown in figure 5. Geologic sections based on the results of test drilling are shown in figures 6-10.

From 6 million to about 2.5 million yrs ago, streams flowing across the Ogallala plain deepened their valleys. During Pleistocene time the advance and retreat of glaciers in eastern Nebraska alternately dammed and released the eastward-flowing streams. Pleistocene gravels associated with the damming of the streams are found in the Republican Valley, along the Keith-Lincoln county line, and in southeastern Lincoln County. During late Pleistocene time, wind-deposited loess blanketed the area. Loess thicknesses range from 0 ft, adjacent to the Republican River, to more than 200 ft in southeastern Lincoln County.

During the last 10,000 yrs, winds have reworked Pleistocene and Ogallala materials and deposited a layer of fine sand from 0 to 30 ft thick over much of southern Lincoln and northern Hayes counties. Streams incising their valleys into the same materials have deposited their sediment loads as alluvium in the valleys.

Climate

The climate of the study area is typical of regions within large continents in the mid-latitudes. It is characterized by irregularly distributed precipitation, low humidity, hot summers, and severe winters. Short-term weather variations result from cyclonic activity and frequent invasions of highly contrasting air masses.

The average temperature of the warmest month,

Table 1. Significant water-bearing and associated geologic units in the study area

System	Series	Geologic unit		Lithology	Usefulness as an aquifer
Quaternary	Holocene and Pleistocene	Alluvium		Sand, gravel, silt, and clay	Yields small to large quantities of water in valleys of major streams.
		Terrace deposits		Sand, gravel, silt, and clay	Yields small to large quantities of water in valleys of major streams.
		Dune sand		Very fine to course sand	Upland deposits generally above the water table
		Loess and sand		Silt, in part calcareous and/or sandy at base	
Tertiary	Miocene	Ogallala Group		Sand, sand and gravel, sandstone, silt, clay, and siltsone; poorly to well consolidated; much calcium carbonate	Principal aquifer; yields moderate to large supplies of water to wells.
	Oligocene	White River Group	Brule Formation	Silt, siltstone, clay and claystone, in part slightly to very calcareous	Not tapped by any wells in study area. Probably would yield small quantity of water to wells.
			Chadron Formation	Clay and claystone; in places a thin white sand at base	Not tapped by any wells in study area. Probably would yield water for wells only where fractured.
Cretaceous	Upper Cretaceous	Pierre Shale		Dark-colored shale; weathered top is mostly yellow-orange and is referred to as "ochre"	Not tapped by any wells in study area. Probably would yield water for wells only where fractured.
		Niobrara Formation		Orange-white to dark grayish brown chalk, limestone, and shale	Not tapped by any wells in study area. Probably would yield water for wells only where fractured.

July, ranges from 75 to 78° F. January, usually the coldest month, averages from 25 to 28° F. Extreme temperatures are more descriptive of the climate than the means. Winter minimums of –38° F and summer maximums reaching 116° F have been recorded. The periodic invasion of continental tropical air masses and Chinook winds from the Rocky Mountains results in frequent warm weather during the winter that often does not occur farther east in the state. Summers are often very hot with desiccating winds caused by hot, dry, tropical air masses from the desert Southwest.

The growing season, the period between killing frosts, generally lasts from 150 to 160 da. The last killing frost in spring usually occurs during the first week in May, and the first killing frost in autumn usually occurs during the first week of October. The occurrence of these first and last killing frosts is quite variable, however, and may occur a month earlier or later than the average dates.

Mean annual precipitation ranges from approximately 20 in. in the northwestern part of the study area to about 22 in. in the southeast. Annual precipitation, however, may vary as much as 50 percent from the mean. Droughts can last for several years. Within the last century, droughts have occurred in the mid-1890s, the 1930s, mid-1950s, and the mid- to late 1970s. These droughts were accompanied by warmer than average summer temperatures and desiccating winds, which contributed to greater potential evapotranspiration (ET) rates and more intense drought conditions. Short-term growing season deficiencies of precipitation, which are not apparent from annual or monthly data but have serious effects on dryland crop production, are frequent.

Seventy-five to eighty percent of the annual precipitation typically occurs during April through September, but usually is irregularly distributed. Precipitation during this period is mainly the result of convective activity (thunderstorms) that causes the distribution of rainfall to be irregular. Precipitation from October through March is generally more uniform throughout the study area because of its cyclonic or frontal origin. Snowfall averages between 25 and 30 in. annually, but accounts for only a small part of the normal annual precipitation.

Annual potential ET in the study area nearly always exceeds annual precipitation. Potential ET averages more than 40 in., whereas precipitation is only 20 to 22 in. Monthly precipitation surplus over potential ET is common during November through May, and deficits occur during June through October. Low humidity, periods of persistent wind, and a high incidence of sunshine contribute to large ET rates, which lead to frequent soil-moisture deficits.

Soils

The major soil characteristics result from deposition of loess in a semiarid-to-subhumid climate with a grassland regime. This produces relatively thin, dark, granular top soils with substantial quantities of organic matter and soluble bases. Many of the soils,

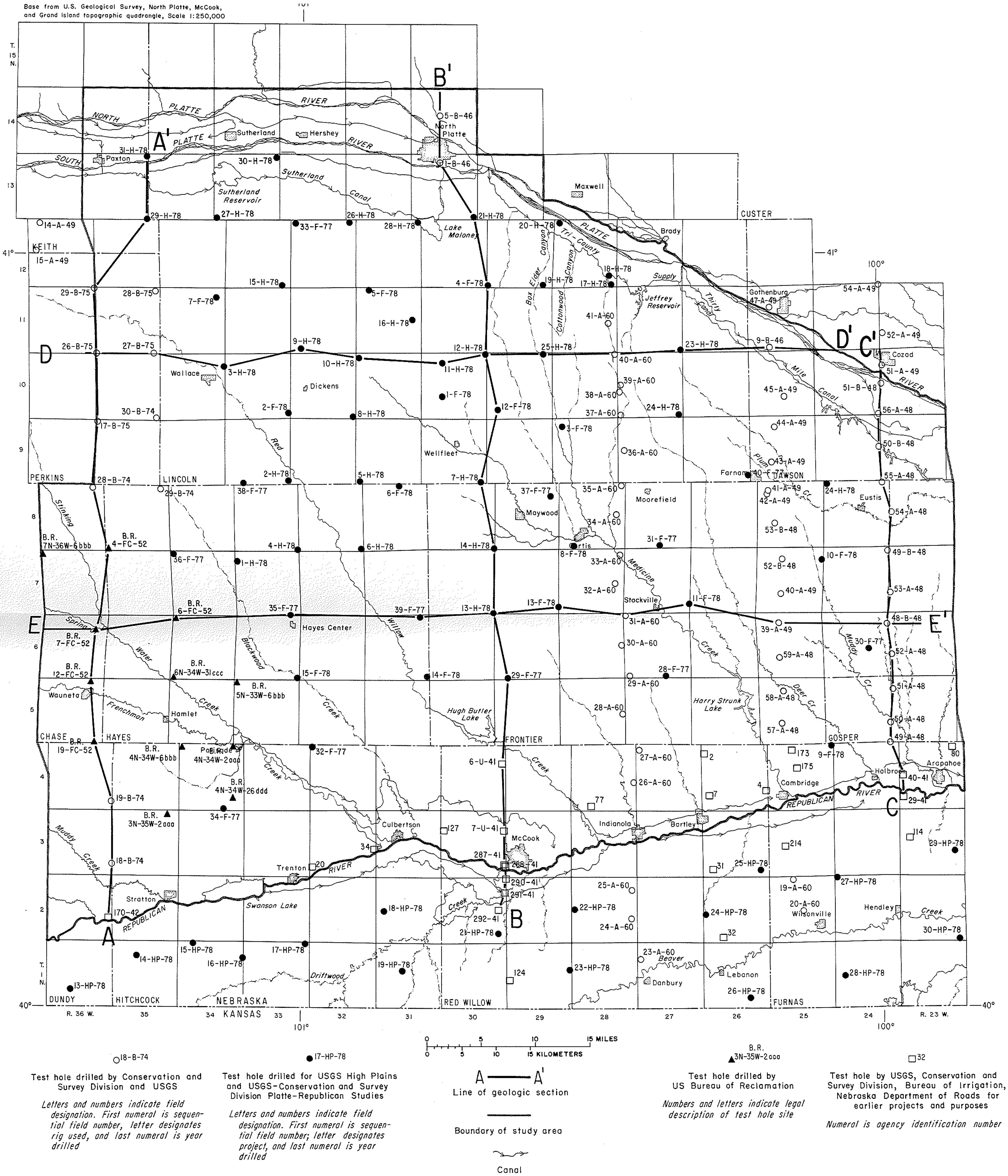


Fig. 5. Location of test holes and hydrogeologic sections.

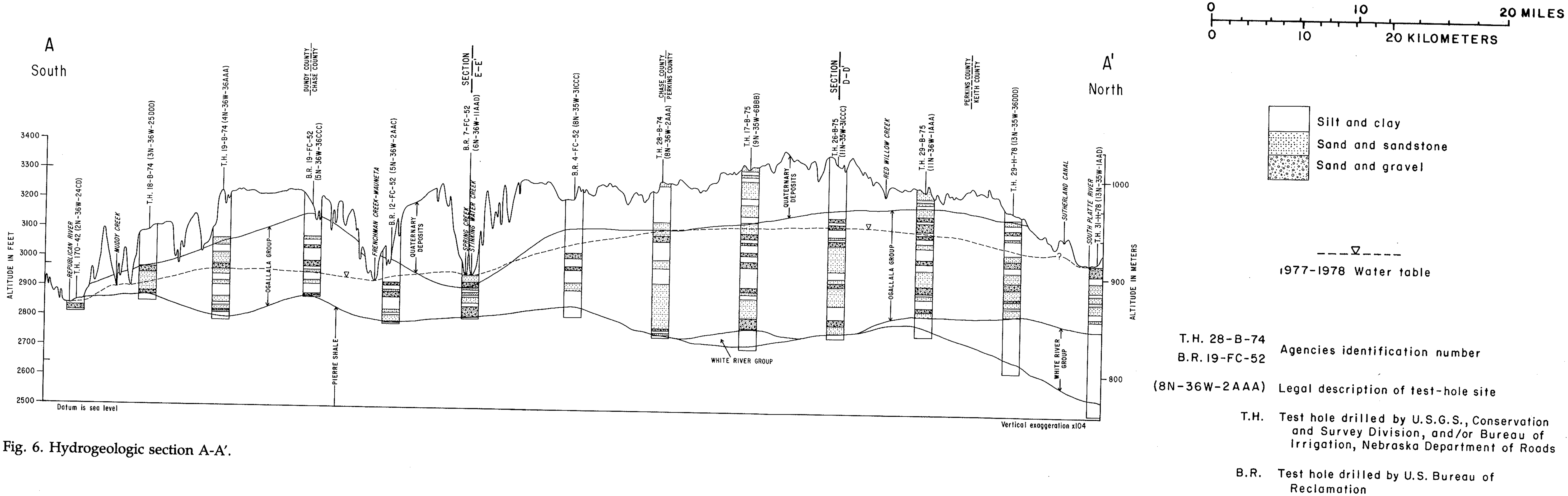


Fig. 6. Hydrogeologic section A-A′.

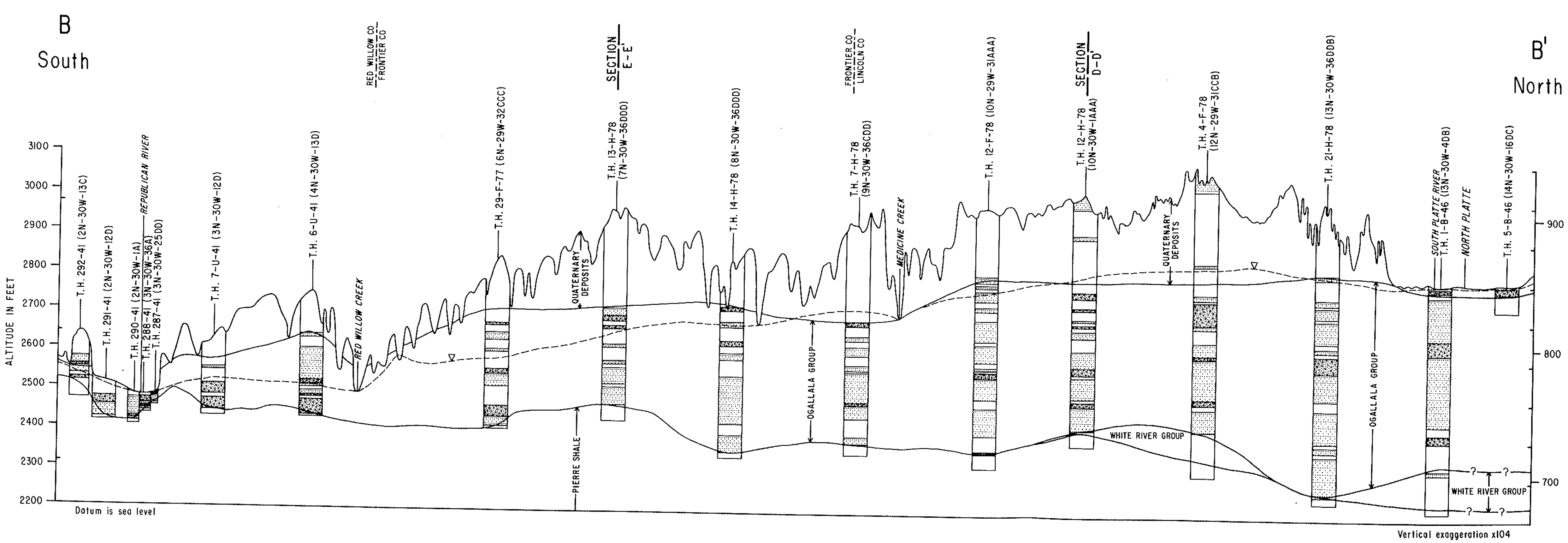


Fig. 7. Hydrogeologic section B-B′.

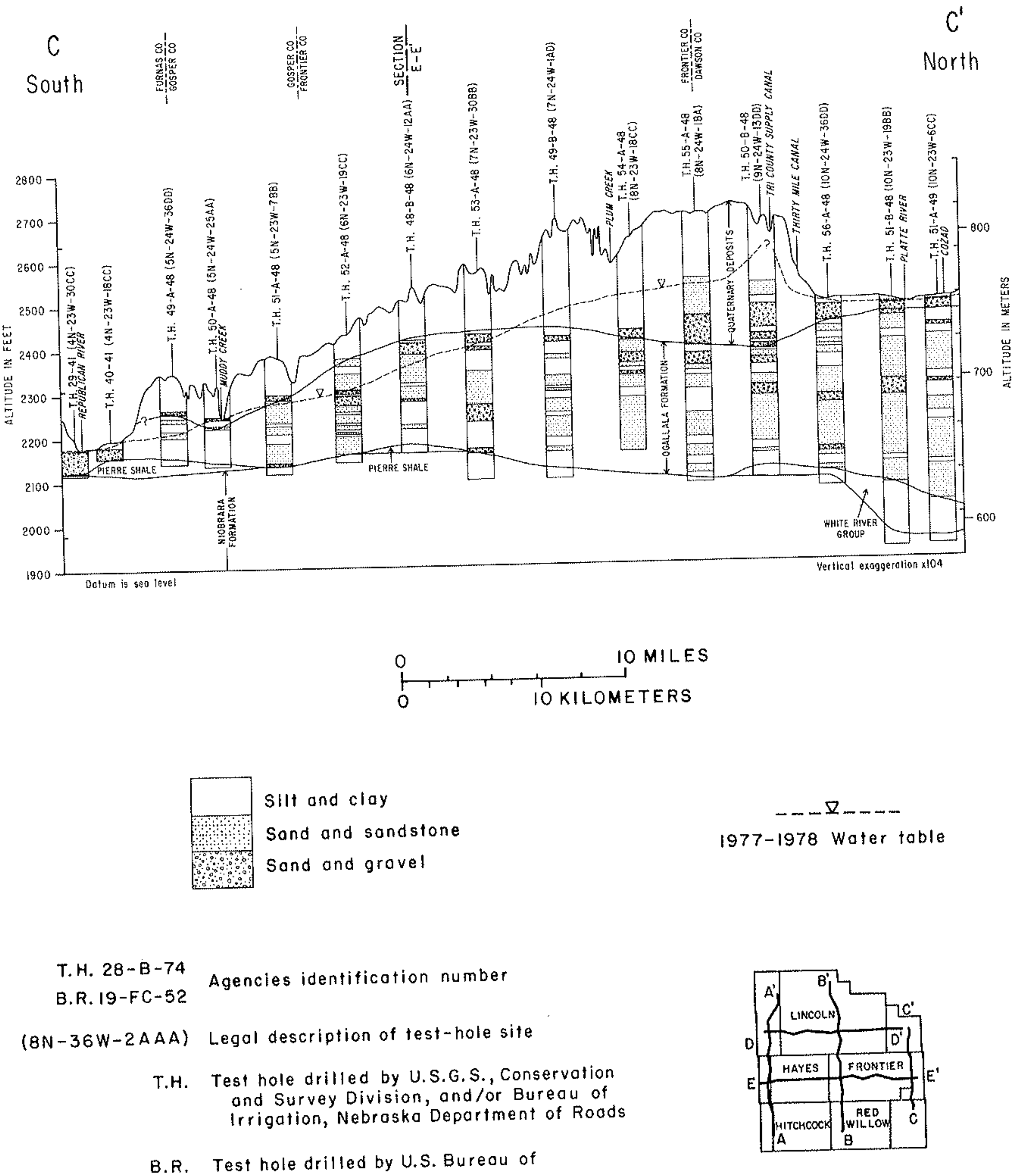


Fig. 8. Hydrogeologic section C-C'.

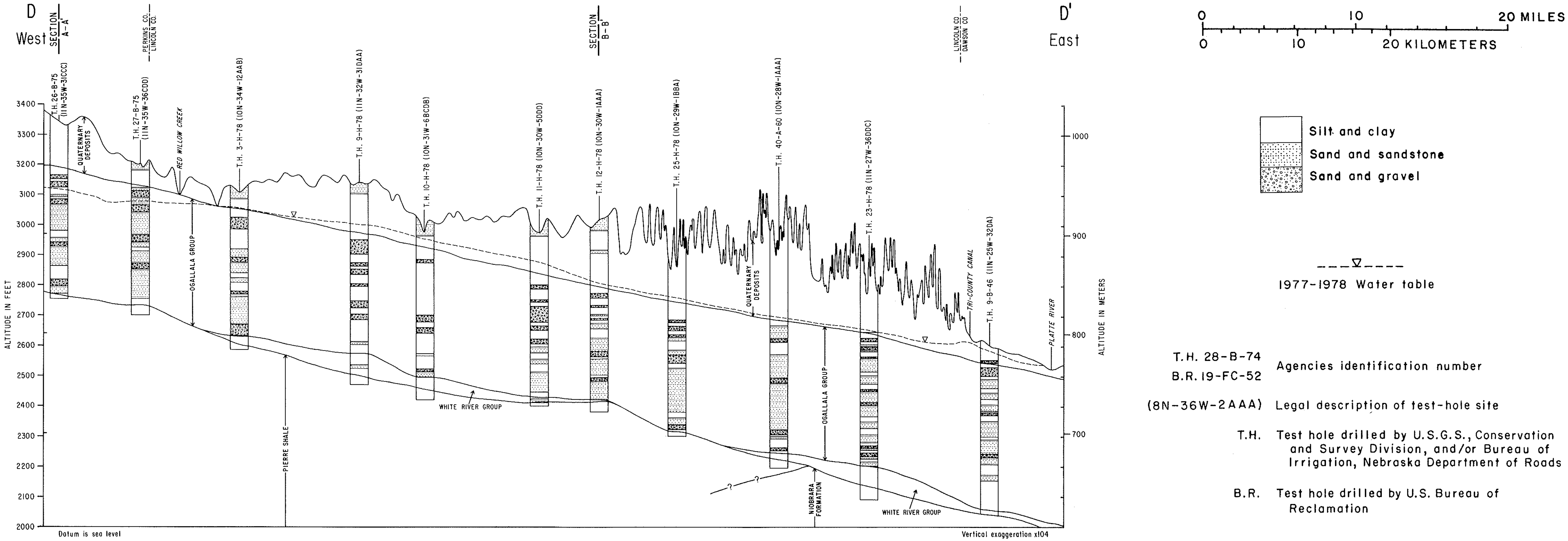


Fig. 9. Hydrogeologic section D-D′.

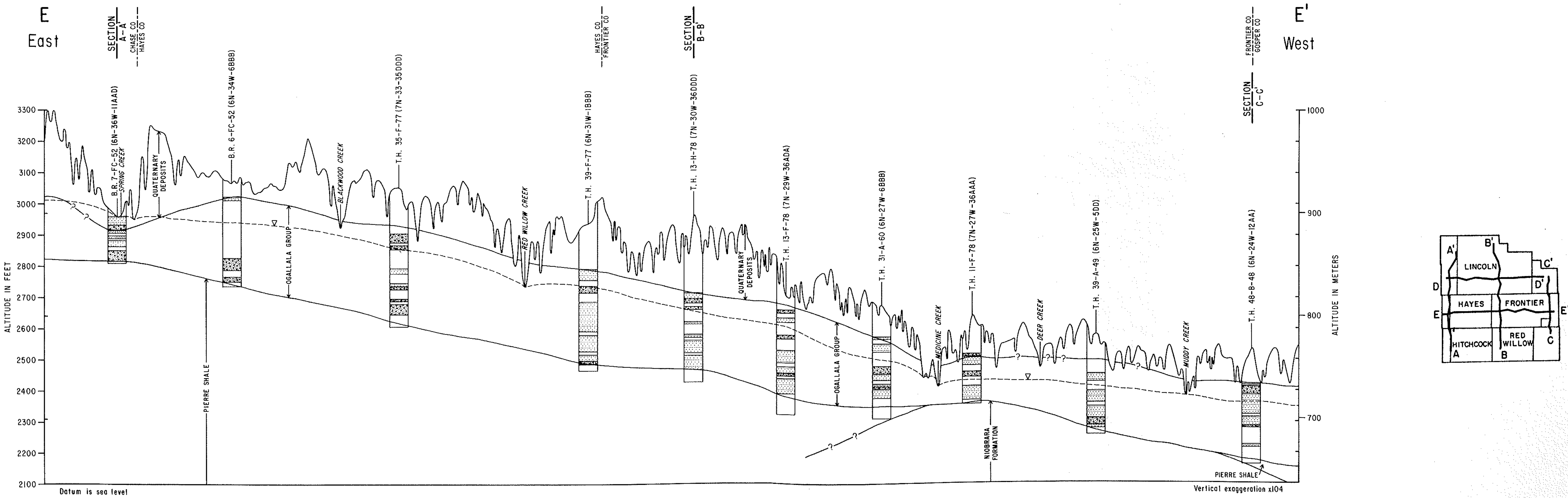


Fig. 10. Hydrogeologic section E-E′.

particularly in the uplands, possess an argillic horizon, which is an accumulation of clays in the upper subsoil resulting from downward movement of fine-grained materials.

The topography and soils are closely related in the study area. Two similar associations are the predominant soils of the dissected plains region—the Colby-Ulysses and Coly-Uly associations, which are combined in figure 11. These soils are formed on loess, have a silt-loam texture, and exhibit minimal soil development. Slopes in this area range from 10 to 60 percent, resulting in high runoff potential.

The flat to slightly sloping uplands (0 to 6 percent) are covered by three major associations: the Holdrege-Hall, Kuma-Keith-Goshen, and Rosebud-Alliance-Kuma associations. These associations differ essentially only in their soil-moisture regime. Such soils have silty loam topsoils and silty clay loam subsoils with an argillic horizon and have a moderate to moderately low permeability.

Much of the study area, particularly in the northwestern part, is covered by soils formed on eolian sands, including the Valentine and Valent-Tassel associations. These soils are weakly developed and highly permeable, occupying a short, choppy dunal topography. Surrounding these sandy soils is a zone of soils transitional to the uplands soils formed in loess. Such soils range from loams to loamy fine sands and consist of the Jayem-Sarben and Vetal-Hersh associations. These soils have rather high permeabilities and are present on nearly level to rolling terrain.

Bottomland and terrace soils are not extensive in the study area, as shown in figure 11. Along the Republican River and its tributaries, the terrace and bottomland soils are principally silty Hobbs-Hord-Cozad, Bankard-Las-Glenberg and McCook-Munjor-Inavale associations. In the Platte Valley, some sandy bottomland soils also are present along with those that are silty; these belong to the Lawet-Wann-Lex Association.

The agricultural potential of the study-area soils is quite variable. The dissected uplands usually are too steep and the topsoil too thin to support continual cultivation. The sandy soils are subject to wind erosion if the vegetative cover is removed. Soils developed on loess on the flat interfluves are quite productive if irrigated. Terrace and better drained bottomland soils are capable of supporting cultivation and potentially are the most productive soils of the study area.

Natural Vegetation

A large part of the study area remains in native vegetative cover. More than 50 percent of the total land area is rangeland. Much of the study area is too steep or has soil limitations that are too severe to support sustained cultivation.

The native vegetation consists principally of two major grassland types. One is mixed prairie on the loess or silty soils and the other is the grassland typical of the Sand Hills. To describe these grasslands as climax vegetation is questionable because changing climatic conditions result in constant transition. The variation in grass types that may dominate a community from time to time is an expression of both short- and long-term weather cycles, as well as grazing and management practices.

Weaver and Albertson (1956) divided the natural vegetation of the loess-covered areas into three principal plant communities. The community present on the hilltops consists of short grasses capable of thriving in deficient soil-moisture conditions and is represented by blue grama and lesser stands of buffalograss. Tall and mid-sized grasses, similar to those of the true prairie, occupy the bottom of ravines, low terraces, and lower slopes of the hills, where more moisture is available. Here the dominant grasses are big bluestem, side-oats grama, and western wheatgrass, with smaller amounts of switchgrass and Canada wild-rye. A third community, which is present on hill slopes, consists of a two-layered complex formed from the union of the two adjoining plant communities, with the addition of some little bluestem. In this community, buffalograss, the grama grasses, the bluestems, and switchgrass thrive during the warm season; western wheatgrass and Canada wild-rye are more common during the cool season.

The Sand Hills vegetation differs significantly from the mixed prairie of the loess uplands in that the root systems of grasses in the sandy soils are much more extensive laterally and may extend downward 9 ft or more (Weaver and Albertson, 1956). The most characteristic Sand Hills grassland community is the bunch grass. This consists of little bluestem, sand bluestem, prairie sand reed, and needle-and-thread grass. Nongrasses, which are common in this community, are small soapweed, bush morning-glory, sand cherry, and prairie rose.

Several other types of vegetation occur in the Sand Hills. The blowout community (Weaver and Albertson, 1956) is the first vegetation established in stabilized blows and consists of blowoutgrass, lance-leaved psoralea (a legume), and many herbaceous nongrasses with fleshy root systems that help stabilize the sand. The Sand Hills muhly community occurs in sandy wastes caused by fire or by overgrazing and trampling. It is a successor to blowoutgrass. The wet meadows are occupied by a complex community consisting of a dense cover of the common Sand Hills species, as well as bluejoint reedgrass, sedges, tall forbs, swamp milkweed, and many other species.

Deciduous woodlands border the perennial streams. The dominant native species are sandbar willow, black willow, and cottonwood. Introduced species, such as American elm, hackberry, and red and green ashes, also are present.

Land Use

Approximately 90 percent of the area is used for ranching and farming, with the rest consisting of all

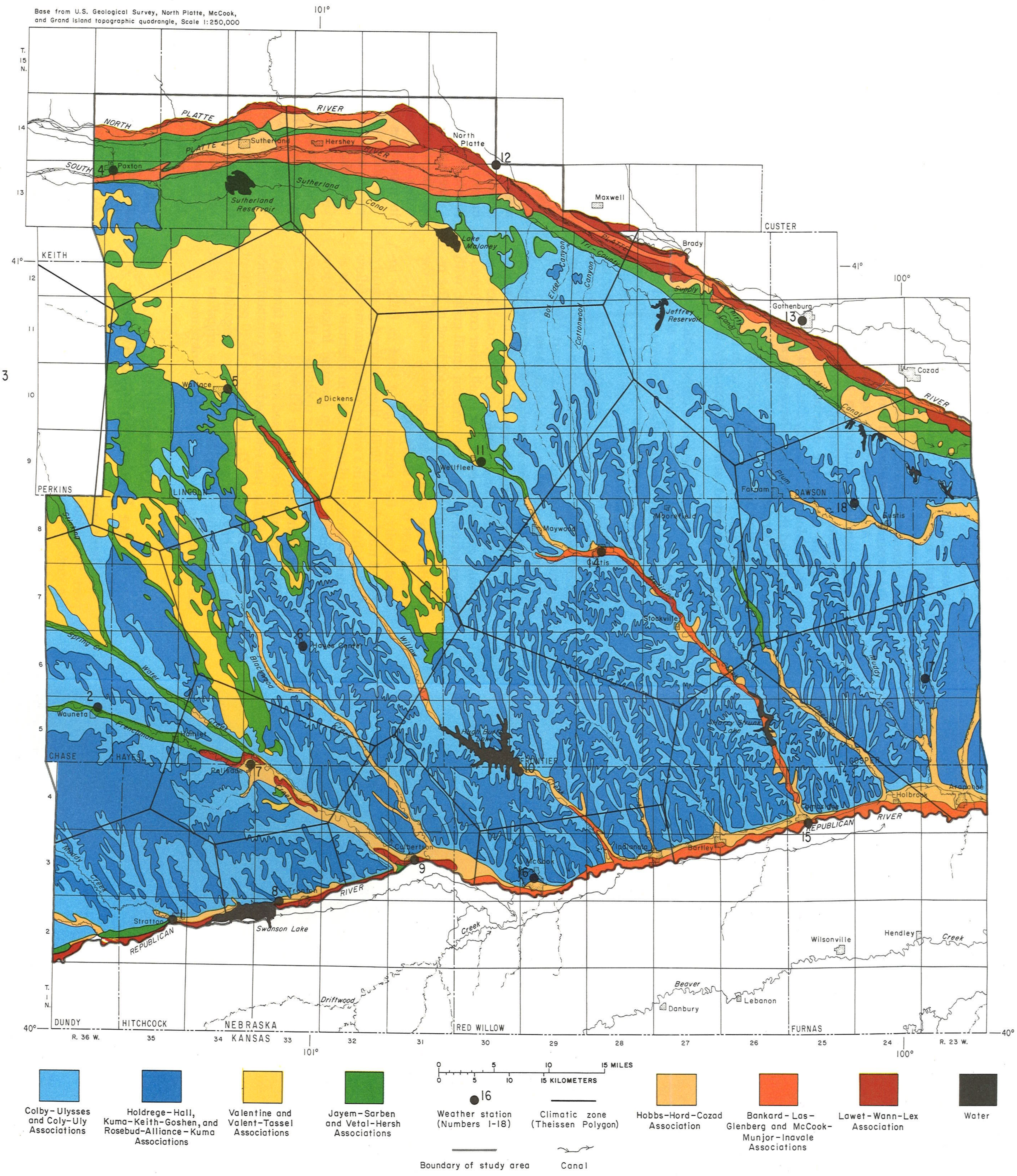


Fig. 11. Soil groups generalized according to hydrologic properties and climatic polygons (modified by J. T. Dugan).

other cover and uses, including roads and railroads, surface water, woodland, and urban uses. The aggregated generalized land use of the 12 counties in the study area is shown in figure 12.

Pasture and range is the predominant land use in the study area, ranging from about 48 to slightly more than 50 percent of the area from 1935 through 1978. Small increases in pasture and range have occurred at the expense of cultivated land since the early to mid-1950s. Also, removal of significant amounts of marginal land from cultivation accounts for some changes in land-use percentages. Soils, topography, and climate dictate the distribution and extent of rangeland. Most of the highly dissected loess-mantled uplands and the Sand Hills have been left as natural grassland vegetation. Since the adoption of center-pivot irrigation in the study area during the early 1970s, some of the native grassland in both terrains has been converted, at least temporarily, to cultivated crops.

Acreages in cultivated row crops, which are primarily corn and grain sorghum, have shown the greatest variability through time. Following World War II, total acreage in dryland corn declined significantly; but since 1970, as irrigated acreage increased, so also has acreage in row crops (fig. 12). Much of this increase has occurred where center-pivot irrigation is used in the uplands for the production of corn. Grain sorghum accounts for only a small part of the row crops under cultivation in the study area.

Small grains are the second most common type of cultivated crop, but the acreage has declined somewhat since 1952. From 1946 until 1952, total acreage of small grains exceeded that of all other crop types. Winter wheat is the most common small grain, with oats, rye, and barley accounting for most of the remainder. The major wheat-growing area is in the western part of the study area.

Historically, the percentage of land in fallow increased until the late 1960s, then declined gradually. Much of this land is in a winter-wheat, summer-fallow rotation—wheat is planted only in alternate years as a soil-moisture conservation practice. Irrigated row crops have increased in the uplands at the expense of small grains and summer fallow.

The percentage of land used for growing tame hay, principally alfalfa, has remained nearly constant since the early 1950s (fig. 12). Twenty-five to 30 percent of the tame hay is irrigated alfalfa. Most irrigation is in the Platte River valley; less extensive irrigation is in the Republican River valley and its tributaries.

Description of the Hydrogeologic System

The hydrogeologic system, as defined for this report, was divided for analysis into four components: the surface-water system, soil zone, unsaturated zone, and saturated zone. Mathematical models have been constructed to simulate three of these components. However, neither appropriate data nor an adequate mathematical model is available for simulating the unsaturated zone.

Surface-water System

The surface-water system consists of streams, canals, and reservoirs. This system is complex and interconnected and connects with other components of the hydrogeologic system. Examples are the connections among the aquifer, streams, reservoirs, and canals, which provide passageways for diversions and return flows to the streams or reservoirs. A third example of this complex interconnection is the seepage of surface water from canals and reservoirs recharging the aquifer or becoming baseflow to the streams.

Streams

There are two major river systems within the study area. The Platte River system, consisting of the North Platte, South Platte, and Platte rivers, lies along the northern border. The Republican River lies along the southern border. The major streams and tributaries, canals, reservoirs, and sites of diversions and return flows are shown in figure 13. Tributaries to these streams, especially those to the Republican River, often are dry during the irrigation season. Other streams carry only infrequent runoff from precipitation.

A schematic diagram of the surface-water system in and near the study area is shown in figure 14. It shows the perennial streams, stream-gaging stations, reservoirs, and canal diversions and returns. The mean annual flows at stream-gaging stations, mean annual inflows from tributary streams, and mean annual canal diversions and returns also are shown.

Seepage was estimated from streamflow measurements (where all observable inflows and outflows of water were measured) on the Republican River and its tributaries and the Platte River system during fall 1978 and spring 1980. The results of these measurements are published in "Water Resources Data for Nebraska—Data Report NE 79-1 and NE 80-1" (U.S. Geological Survey, 1980 and 1981). The flows measured during fall 1978 were extremely small because precipitation had been minimal during the summer and fall; however, the flow measurements during spring 1980 were made after near normal amounts of precipitation occurred during the previous months. The seepage estimates approximate the groundwater contribution to the surface-water system. Therefore, extreme precipitation or its lack before or during the flow measurement affects the estimates.

Data on seepage gains or losses and average streamflows can be used to improve the understanding of the stream-aquifer relation. For example, streamflows in Frenchman Creek have declined during the past 20 yrs, apparently because of one or more of the following: 1) additional groundwater development in upper reaches of this stream; 2) changes in farming practices (minimum tillage and other conservation practices); and 3) less-than-average precipitation.

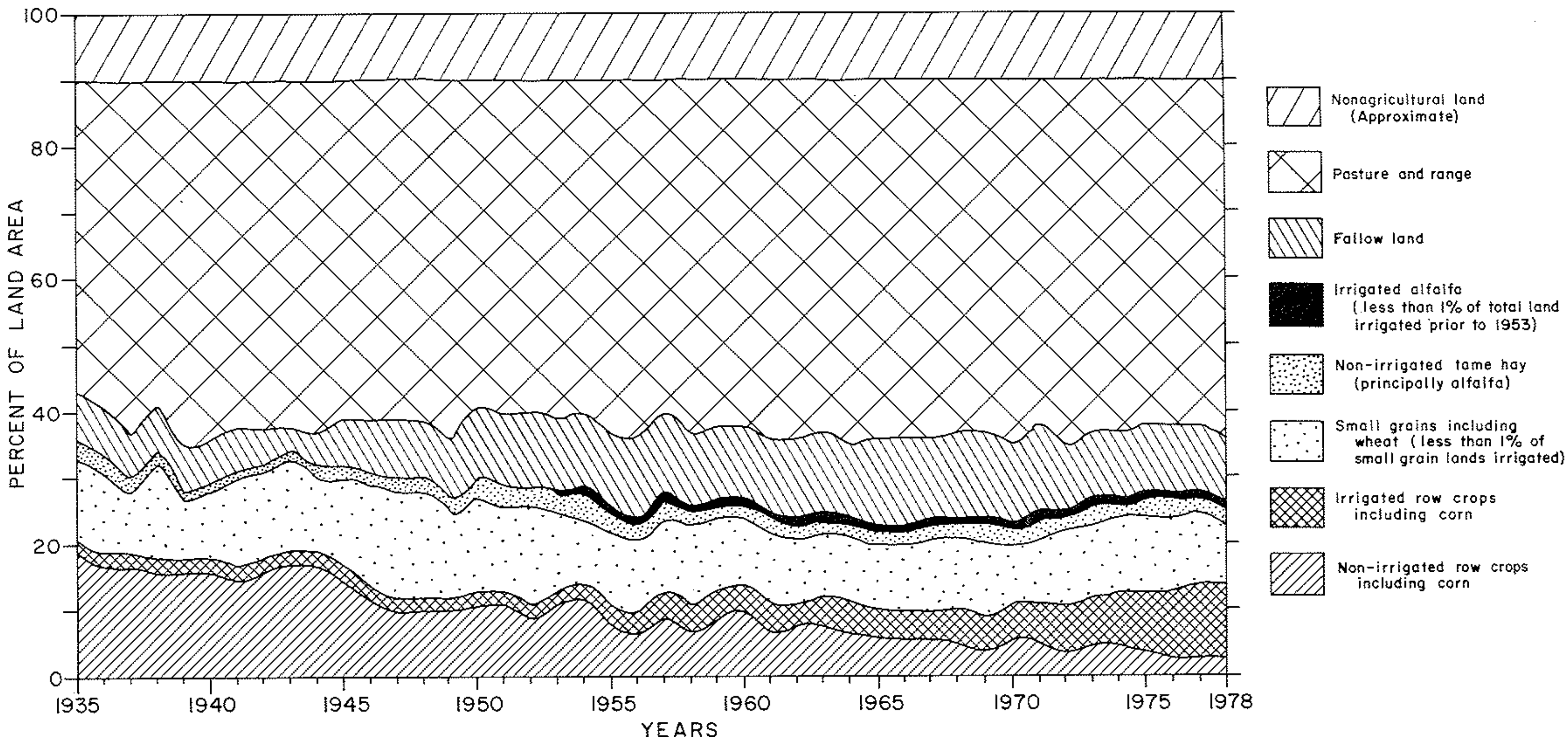


Fig. 12. Generalized land use (compiled from Nebraska Department of Agriculture data).

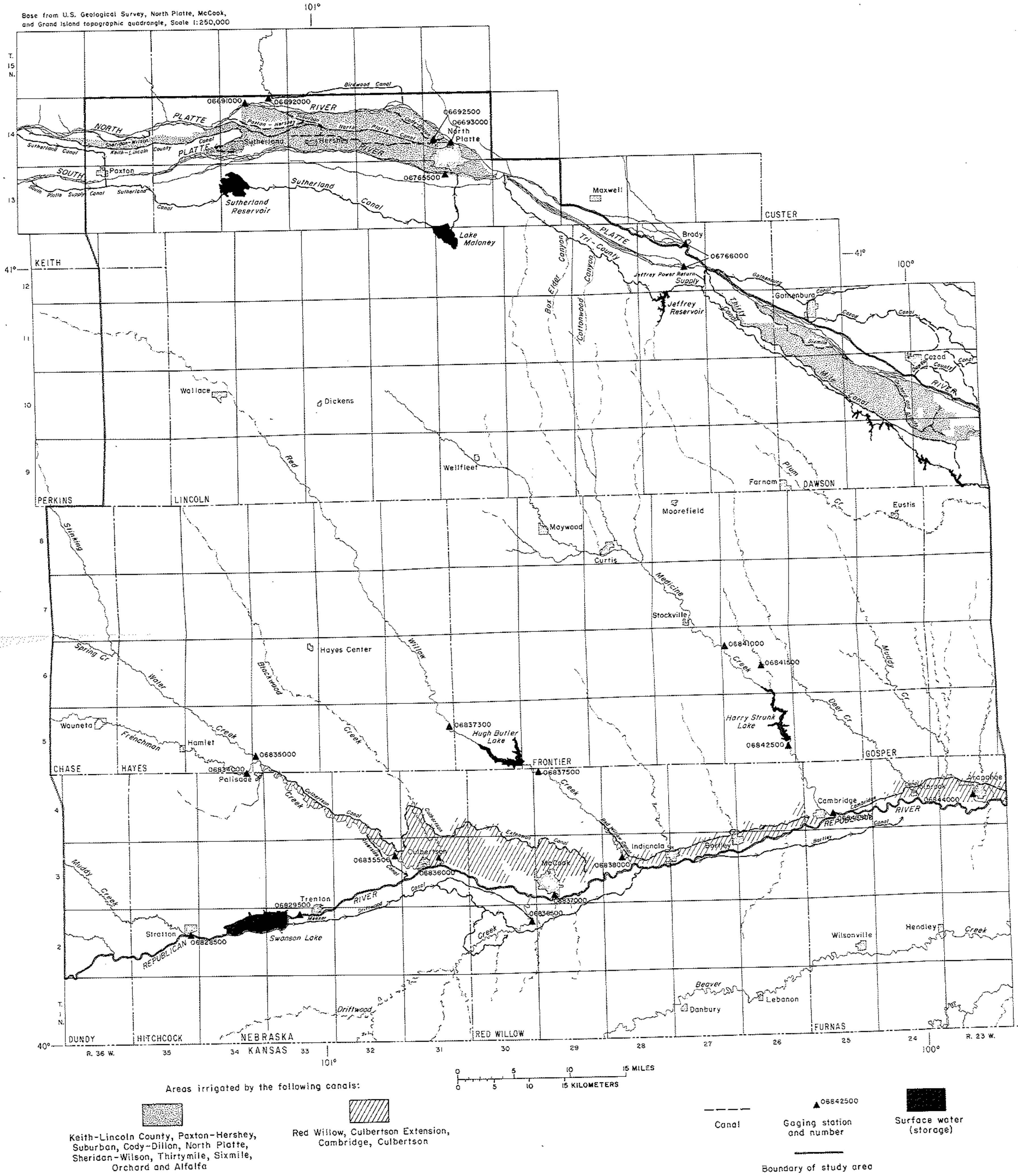


Fig. 13. Surface-water system with location of canals, reservoirs, surface-water irrigated lands, and gaging stations.

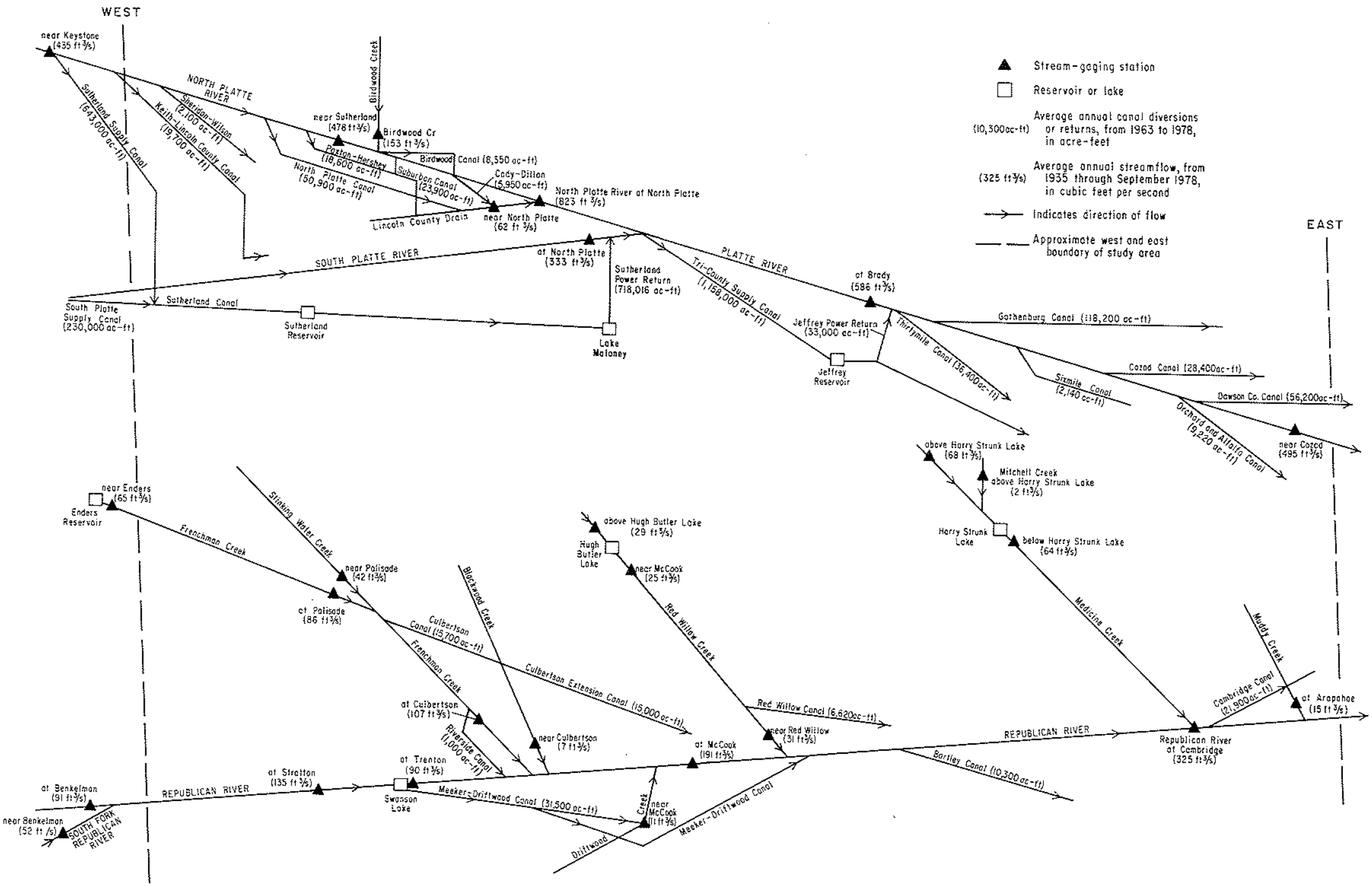


Fig. 14. Schematic diagram of the surface-water systems.

Canals

The surface-water canals in the study area comprise a complex distribution system for irrigation, cooling at a steam plant, and electric-power generation. Water is diverted by seven canals from the North Platte River between G. P. Kingsley Dam, which is west of the extended study area, and North Platte, Nebraska (fig. 13). These canals, from west to east based on their diversion points, are: Sutherland, Keith-Lincoln County, Sheridan-Wilson, North Platte, Paxton-Hershey, Suburban, and Cody-Dillon. Outside the study area on the north side of the North Platte River, Birdwood Canal, which diverts from Birdwood Creek and supplies irrigation water to land north of the North Platte River, returns unused water to the North Platte River. The main canals and areas irrigated by diverted surface water are shown in figure 13. The irrigation laterals and field-distribution systems are not shown. A schematic diagram of the surface-water system (fig. 14) shows the diversion sequence and gives the total mean annual volume of diversions in acre-feet per year.

The South Platte Supply Canal diverts water from the South Platte River west of the study area. This canal flows on the south side of the South Platte River until it joins the Sutherland Canal. Together, the diversions from these two canals are stored at Sutherland Reservoir, where they provide cooling water for condensers on a steam power plant. Further east at Lake Maloney, water from the Sutherland Canal (outlet canal) is stored for release for power generation at the North Platte power plant. Water passing through the plant is returned to the South Platte River.

East of the confluence of the North Platte and South Platte rivers at North Platte, Nebraska, the Tri-County Supply Canal diverts water from the Platte River. This canal flows primarily on terraces of the Platte River adjacent to the uplands on the south side of the Platte River. Several intermittent streams flow into this canal, and one major reservoir, Jeffrey Reservoir, is in this area. Further east from Jeffrey Power Return, where water is returned to the Platte River, three canals divert irrigation water to the south side of the Platte River. From west to east these canals are Thirtymile, Sixmile, and Orchard and Alfalfa. Also, several small reservoirs associated with the Tri-County Supply Canal are located in this area.

On the north side of the Platte River in Lincoln and Dawson counties, three canals, Gothenburg, Cozad, and Dawson County, divert water from the Platte River for surface-water irrigation. Before 1974, the Gothenburg Canal also was used to provide cooling water for power generation.

The U.S. Bureau of Reclamation has developed six canal systems with four storage reservoirs for providing surface-water irrigation and flood protection on the Republican River and its tributaries within or near the study area. From west to east, Culbertson, Culbertson Extension, and Red Willow canals are within the study area on the north side of the Republican River; the Cambridge Canal has its western part within the study area on the north side of the river. Two canals, the Meeker-Driftwood and Bartley, divert water to the south side of the Republican River just outside the study area.

The Riverside Canal has been operating in the Republican River drainage area since 1894. This canal, developed by mutual agreement among farmers along the canal, diverts approximately 1,000 acre-ft of water annually from Frenchman Creek northwest of Culbertson, Nebraska. It provides irrigation water for about 500 acres along its 4-mi length.

Table 2 lists data on the average amounts of water diverted or returned to a stream and on the acres irrigated with canal water. This information was compiled from 1963-1978 data, when all the canals in the system were in operation.

Reservoirs

Six primary reservoirs are within the study area, and several small reservoirs are along the Tri-County Supply Canal. The location and areal extent of these reservoirs are shown in figure 13. The approximate surface area, first year of operation, and seepage losses for each of these reservoirs are listed in table 3.

The Sutherland Reservoir, Lake Maloney, and Jeffrey Reservoir in the Platte River drainage system are used for power generation. However, Swanson Lake, Hugh Butler Lake, and Harry Strunk Lake in the Republican River drainage system provide storage of irrigation water for the Meeker-Driftwood, Red Willow, and Cambridge canals, respectively. Enders Reservoir, west of the study area, is used for storing irrigation water on Frenchman Creek for the Culbertson and Culbertson Extension canals.

Surface-water Seepage Losses

A substantial part of the water diverted from the Platte and Republican river systems for irrigation and power generation is lost by seepage to groundwater storage or to streams. Seepage losses are difficult to estimate and require complex calculations because of the non-uniformity or inadequacy of available data. Seepage losses also are dependent upon the soil, particularly its permeability. To determine seepage indirectly several types of information are necessary. The following data typically are required to estimate seepage:

$$(\text{Seepage} = 1 + 2 - 3 - 4 - 5)$$

where

(1) is stream diversions or gaged inflow into the system;
(2) is an estimate of ungaged (unmeasured) inflow into the system;
(3) is irrigation diversions from the system;
(4) is an estimate of ET losses from the system; and
(5) is return flows or outflows from the system.

Estimates of seepage made using this equation are assumed to be accurate within 15 percent of the actual

Table 2. Canal diversions and returns

[Sources: Nebraska Department of Water Resources (1935-1978) and U.S. Bureau of Reclamation unpublished data]

Canal	Water use[a]	First year of operation	Average acres irrigated	Average annual diversion 1963 to 1978: Irrigation (acre-feet)	Average annual diversion 1963 to 1978: Power (acre-feet)	Average annual return 1963 to 1978 (acre-feet)
North Platte and South Platte Canals[b]	I	--------	27,000	120,000	--------	--------
Sutherland Supply[c]	P	1935	--------	--------	643,000	--------
South Platte Supply	P	1935	--------	--------	230,000	--------
Sutherland (total)		--------	--------	--------	873,000	668,000
Tri-County	I,P	1941	--------	552,000	606,000	606,000
Jeffrey Power	P		--------	--------	--------	33,000
Gothenburg	I,P	1891	(d,e)	5,700	(e)72,500	72,500
Cozad	I	1895	(d)	28,400	--------	--------
Dawson County	I	1895	(d)	56,200	--------	--------
Thirtymile	I	1926	3,560	36,400	--------	--------
Sixmile	I	1895	1,170	2,140	--------	--------
Orchard and Alfalfa	I	1896	1,270	9,220	--------	--------
		Republican River basin				
Culbertson	I	1935	9,550	15,700	--------	--------
Culbertson Extension	I	1961	11,700	15,000	--------	--------
Meeker-Driftwood	I	1952	(f)	31,500	--------	--------
Red Willow	I	1963	4,980	6,620	--------	--------
Bartley	I	1954	(f)	10,300	--------	--------
Cambridge	I	1951	(g)16,900	21,900	--------	--------

(a) I, irrigation; P, power generation.
(b) Canals are between North Platte and South Platte rivers and are within or partially within the study area. Canals and first year of operation are: North Platte, 1884; Sheridan-Wilson, 1891; Keith-Lincoln County, 1895; Paxton-Hershey, 1895; Cody-Dillon, 1895; Suburban, 1895.
(c) South Platte Supply Canal flows into Sutherland Canal.
(d) Water is diverted from the Platte River to irrigate land outside the study area.
(e) Last year for power diversions was 1973.
(f) Water is diverted from Swanson Lake for the Meeker-Driftwood Canal and the Republican River for the Bartley Canal to irrigate land outside the study area.
(g) Part of the irrigated land supplied by the Cambridge Canal is outside the study area.

Table 3. Average annual seepage losses from primary reservoirs

[Sources: Nebraska Department of Water Resources (1935-78) and U.S. Bureau of Reclamation unpublished data]

Reservoir or lake	Surface area (acres)	First year of operation	Seepage losses: Beginning of operation to 1978 (acre-feet)	Seepage losses: 1963-78 (acre-feet)
Sutherland	2,800	1935	62,100	67,800
Maloney	1,680	1936	21,500	13,700
Jeffrey	512	1941	(a)	(a)
Swanson	4,974	1953	38,100	48,400
Hugh Butler	1,629	1961	5,000	4,900
Harry Strunk	1,850	1950	7,300	7,500

(a) Seepage losses for Jeffrey Reservoir are specified as canal losses; that is, losses are in acre-feet per mile (see table 4).

Table 4. Average annual seepage losses from canals

Canal	Length of canal[a] (miles)	Seepage losses (acre-feet) Beginning to 1978	Seepage losses (acre-feet) 1963-78	Seepage losses per mile (acre-feet) Beginning to 1978	Seepage losses per mile (acre-feet) 1963-78
	Platte River basin				
Sutherland Supply and South Platte Supply	50.0	51,300	54,700	1,020	1,090
Sutherland (from Sutherland Reservoir to Lake Maloney)	18.6	34,000	34,100	1,680	1,830
Sutherland (from Lake Maloney to the South Platte River)	3.0	3,000	3,000	1,000	1,000
Tri-County Supply (from diversion point to Jeffrey Hydroelectric Plant)	21.0	41,000	56,500	[b]44.7	[b]61.2
Tri-County Supply (from Jeffrey Hydroelectric Plant to Johnson Lake	33.0	169,000	155,000	[c]121	[c]111
	Republican River basin				
Culbertson	24.0	6,990	6,090	291	254
Culbertson Extension	44.8	12,900	13,700	289	306
Red Willow	23.6	2,330	2,330	98.6	98.6
Cambridge	9.9	2,060	2,210	209	223

[a] Canal length is only for segment within the study area.
[b] Seepage is in feet. Jeffrey Reservoir and Tri-County Supply Canal within this segment cover 932 surface acres (512 acres for the reservoir and 420 acres for the canal).
[c] Seepage is in feet. The lakes and Tri-County Supply Canal within this segment cover 1,392 surface acres.

values. This accuracy was derived by combining the individual accuracies of the five items above.

Because data for the canals and reservoirs in the study area were not uniform, various computational methods were required. Some required only subtraction of ET from gross system losses. Others, where measured inflows and return flows were provided, required subtraction of irrigation diversions and ET to derive seepage.

ET losses in each system were computed based on pan evaporation at nearby sites. For smaller canal systems, which are likely to have substantial ET from their banks, actual pan values were used in the computations. For larger canals and reservoirs, the ET losses were treated as lake evaporation and the lake-pan evaporation factor of 0.7 (Chow, 1964, p. 11-7) was used to adjust the pan-evaporation value. Precipitation was then subtracted from pan evaporation to derive net evaporation. Evaporation was estimated to be a small part of total canal losses (1 to 2 percent) because of the small surface area. Reservoir losses resulting from evaporation, however, range from 10 to 30 percent of the total losses because of the larger surface area.

The Nebraska Public Power District (NPPD) Sutherland Canal, which began operation in late 1935, receives between 750,000 and 1 million acre-ft of water from two diversions annually, one on the North Platte River at Keystone and the other on the South Platte River between Roscoe and Paxton. About 73 percent of the water comes from the North Platte River (table 2). The stretch of canal from the diversions to Sutherland Reservoir has an average net annual seepage of 51,300 acre-ft for 50 mi of canal, or an annual seepage rate of 1,020 acre-ft per canal mile, about a 6-percent loss to seepage (table 4).

Sutherland Canal flows into Sutherland Reservoir. This reservoir is underlain by sandy loam and gravels, so seepage losses are relatively large. Seepage losses averaged 61,000 acre-ft annually through 1978 (table 3) or more than 22 acre-ft per surface acre (2,800 acres). Lake evaporation accounted for an additional 4,200 acre-ft of loss.

The Sutherland Canal (outlet canal) from Sutherland Reservoir to Lake Maloney is 18.6 mi long and flows over sandy loams and sands. Seepage losses from this reach average 34,000 acre-ft annually, or 1,830 acre-ft per canal mile. Losses from Lake Maloney, which covers about 1,680 acres of predominantly sandy soils, average 21,500 acre-ft or 12.8 acre-ft per surface acre annually. The Sutherland Canal (power canal) return to the South Platte River below Lake Maloney loses an estimated 3,000 acre-ft annually. Average annual seepage losses from the Nebraska Public Power District's Sutherland system total 171,900 acre-ft (tables 3 and 4), or about 20 percent of the total annual diversion. In addition, ET losses account for about a 1-percent loss of the total diversion.

The Central Nebraska Public Power and Irrigation District (CNPPID), which began operations in 1941, annually diverts more than 1.11 million acre-ft of water into the Tri-County Supply Canal (CNPPID, unpublished data). Average annual seepage losses and ET losses of 41,000 and 2,500 acre-ft, respectively, occurred from 1941 through 1978 in the 21 mi between the diversion point and the Jeffrey Hydroelectric Plant. The seepage occurred beneath 932 surface acres of Jeffrey Reservoir (table 4) and 21 mi of canal. The average canal width of the Tri-County Canal is approximately 110 ft.

Data for the canal's reach from the Jeffrey Hydroelectric Plant to Johnson Lake did not allow separation of the reservoir and lake losses from total system loss. Of the average outflow of 1,067,000 acre-ft from Jeffrey Hydroelectric Plant, 33,000 acre-ft is returned to the Platte River at the Jeffrey Power Station, and about 90,000 acre-ft is diverted for irrigation. The remainder, except for seepage losses, is conveyed southeastward by canal to Johnson Lake. An additional 4,400 acre-ft annually enters the system from overland runoff and reservoir capture. Inflow to Johnson Lake averages nearly 763,000 acre-ft per year. After subtracting 33,000 acre-ft for return flows and 90,000 acre-ft for irrigation diversions and adding 4,400 acre-ft for overland runoff, the total losses are calculated to be nearly 172,000 acre-ft. About 3,900 acre-ft of this is the estimated ET loss, or less than 1 percent; but nearly 169,000 acre-ft, or 18 percent of the flow below Jeffrey Hydroelectric Plant, is attributed to seepage. This seepage is distributed over 1,392 surface acres of lakes and approximately 33 mi of canal.

The total seepage loss in the CNPPID system from the diversion point to Johnson Lake is nearly 210,000 acre-ft, or about 18 percent of the diversion plus inflow from runoff.

The Thirtymile, Sixmile, and Orchard and Alfalfa canals lie south of the Platte River primarily in Dawson County. No seepage or delivery data are available for these canals, but irrigation-diversion information is available (table 2). None of these canals have any measured return flow, so the remaining water not diverted for irrigation is assumed to be entirely consumed by ET and seepage.

Another system of six irrigation canals, referred to in this report as "North Platte and South Platte canals," exists between the North Platte and South Platte rivers in Lincoln and Keith counties within the study area (table 2). It is assumed that all water diverted not used for irrigation is lost to ET or seepage.

In the Republican River drainage, the U.S. Bureau of Reclamation's data on diversions and systems losses are available for the six canals—Culbertson, Culbertson Extension, Red Willow, Cambridge, Meeker-Driftwood, and Bartley (fig. 13). In comparison to the Platte diversions, those along the Republican River and its tributaries are small because they are only used for irrigation. Average diversions are listed in table 2, and average seepage losses for these canals, except for Meeker-Driftwood and Bartley canals, which are outside the extended study area, are listed in table 4.

It is apparent from these tables that diversions and seepage losses in the Republican River basin are much smaller than those along the Platte River. The seepage losses, however, do have an effect on local ground-water conditions.

Storage and loss data for the primary reservoirs located in the study area are listed in table 3. Of these reservoirs, seepage losses are largest from Sutherland Reservoir because it is underlain by permeable materials and because of its size. Seepage losses from Lake Maloney are 2 to 4 times larger than seepage losses from Hugh Butler and Harry Strunk lakes, even though these lakes are nearly the same size. These differences may be caused by the presence of relatively more permeable material beneath Lake Maloney. Finally, the seepage losses from Swanson Lake, which is on the Republican River, are much larger than the seepage losses from Hugh Butler and Harry Strunk lakes, which are on tributaries to the Republican River. These differences are caused by Swanson Lake's larger surface area and more permeable base or lake bottom.

Soil Zone

The soil zone consists of the soils from the land surface through the root system of the plant community. Water from precipitation and irrigation that infiltrates into the soil zone can be stored temporarily and then withdrawn by ET or downward percolation to the unsaturated zone. Water also can move upward from the saturated or unsaturated zones under capillarity, which is caused by the attractive force of water for the solid walls of the spaces within the porous media and the surface tension of water. However, for this study the upward movement of water from these other zones is nonexistent.

Hydrologic Properties of the Soils

The soils in the study area have been classified into seven groups (fig. 11) based on hydrologic properties. Each soil group was classified with respect to its texture, topographic position, slope, available water capacity, and average profile permeability. A listing of the hydrologic properties for the soil groups is provided in table 5.

The average available water capacity and profile permeability are important factors in determining the volume of water that can be stored in the soil zone and the volume that percolates downward from that zone. Soils having high permeability generally have small available water capacity (the ability of the soil to hold water for use by plants); soils having high permeability allow water to move downward more rapidly than soils having low permeability. Thus, highly permeable soils have a good potential for recharging the aquifer, if the water is not lost to ET or lateral flow in the unsaturated zone before reaching the saturated zone. In contrast, soils with low permeability and large available water capacity hold more

Table 5. Soil groups and their hydrologic properties

[Source: U.S. Soil Conservation Service (1978)]

Soil group	Topographic position	Texture	Range in slope (percent)	Available water capacity (inches per inch)	Permeability average of soil profile (inches per hour)	Permeability of least permeable horizon (inches per hour)
Holdrege-Hall, Kuma-Keith-Goshen, and Rosebud-Alliance-Kuma Associations	Upland	Silt loam to silty clay loam	0-3	0.21	1.20	1.08
Colby-Ulysses and and Coly-Uly Associations	Dissected upland	Silt loam to silty clay loam	0-45	0.16	1.21	1.08
Hobbs-Hord-Cozad Association	Terrace	Silt loam to loam	0-10	0.17	1.45	1.30
Jayem-Sarben and Vetal-Hersh Associations	Upland high terrace	Sandy loam	0-18	0.13	3.14	2.95
Valentine and Valent-Tassel Associations	Rolling upland	Sand	0-45	0.07	13.00	13.00
Bankard-Las-Glenberg and McCook-Munjor-Inavale Associations	Bottomland	Silty clay loam to loamy sand	0-2	0.16	6.46	0.62
Lawet-Wann-Lex Association	Bottomland	Sandy to sandy loam	0-2	0.13	5.30	1.90

Table 6. Average annual precipitation, in inches, at weather stations

Number in figure 9	Weather station	Average annual precipitation from 1935-1978
1	Stratton	20.06
2	Wauneta	19.34
3	Madrid[a]	19.25
4	Paxton 2W[a]	17.97
5	Wallace 1 ENE	17.90
6	Hayes Center	20.07
7	Palisade	19.62
8	Trenton Dam	18.89
9	Culbertson	20.13
10	Red Willow Dam	19.44
11	Wellfleet 1 SE	20.76
12	North Platte WSO AP[a]	19.02
13	Gothenburg[a]	21.05
14	Curtis	20.10
15	Cambridge	21.39
16	McCook	20.16
17	Elwood 9 SSW	20.93
18	Eustis 2 NW	20.81

[a] Outside the study area.

water in the soil profile, and thus have a low potential for recharging the aquifer.

Factors other than permeability and available water capacity influence the infiltration rates of water. Even though soils having high permeability normally have more rapid infiltration rates and less rapid surface-runoff rates, the intensity of rainfall, amount of water in the soil profile, vegetative cover, and whether the ground is frozen also influence infiltration rates.

Water Requirements of the Vegetation

Different types of plants have different water requirements; therefore, it is necessary to distinguish between natural and cultivated vegetation and between the primary crops. The water requirements of the land-use groups in figure 12 from least to greatest are: fallow; small grains (predominantly wheat, with some oats, barley, and rye); pasture and range; non-agricultural land (which includes urban lands, farmsteads, roads, and woodlands); non-irrigated row crops (corn, soybeans, grain sorghum, sugar beets, and potatoes); irrigated row crops; non-irrigated tame hay (including alfalfa); and irrigated alfalfa.

Input to and Output from the Soil Zone

Precipitation and irrigation are inputs to the soil zone; ET, surface runoff, and deep percolation are outputs from the soil zone.

Monthly precipitation data from 18 weather stations for January 1935 to December 1978 were compiled for this study (National Oceanic and Atmospheric Administration, 1936-1979).

The location of these weather stations is shown in figure 11; the average annual precipitation for each station is listed in table 6. Missing monthly precipitation data were estimated from data at two or three nearby weather stations using equations derived from a regression analysis.

Precipitation zones or Thiessen polygons (Linsley and others, 1958) (fig. 11) were constructed around each weather station to areally distribute the point measurements of precipitation. The area in each polygon is assumed to receive the same monthly precipitation as the weather station.

Both surface water and groundwater are used for irrigation in the study area. Most of the land irrigated with surface water is located in the Platte River and Republican River valleys and is shown on figure 13. Distribution by township of potential irrigable land and land irrigated in 1980 is shown in figure 15.

For land irrigated with surface water between the North Platte and South Platte rivers, it is assumed that 50 percent of the diverted water is applied to the crops and the remaining 50 percent seeps from the canals and their laterals (Nebraska Department of Water Resources, oral communication). This seeped water percolates through the soil zone and recharges the aquifer.

Seepage losses for the remaining lands irrigated with surface water have been estimated and previously discussed (table 4). The seepage losses are based on the volume of diverted water and the soils in which the canals occur. This water percolates through the soil zone or the unsaturated zone or both, and reaches streams or the aquifer.

Other losses from the soil zone are ET, which was estimated using Jensen-Haise procedures (Jensen and others, 1969) for computing potential ET, deep percolation from precipitation and irrigation, and surface runoff. The procedures for computing these and other values will be discussed in "Procedures for Estimating Recharge and Pumpage Data" later in this report.

Unsaturated Zone

The unsaturated zone extends from the base of the soil zone to the water table. Within the unsaturated zone, water may move downward, upward, and laterally, as well as be stored for limited periods. For this study, the unsaturated zone is treated simplistically as a conduit through which water moves without appreciable storage. The assumptions are that all water leaving the soil zone reaches the saturated zone and that lateral movement of water within the unsaturated zone is negligible.

The thickness of the unsaturated zone is determined approximately by determining the distance from the land surface to the saturated zone. For unconfined aquifers, the depth to water in wells can be used to approximate the thickness of the unsaturated zone. Depths to the saturated zone in the study area during 1977-1978 are shown in figure 16. The thickness and types of sediments in the unsaturated zone determine how readily moisture moves to the saturated zone. Hydrogeologic sections A-A′, B-B′, C-C′, D-D′ and E-E′ (figs. 6-10) show the variations in thickness of sediments of the unsaturated zone.

In incised stream valleys, the depth to water ranges from 0 to 50 ft, and in the uplands between drainageways it is 200 ft or more. In parts of southeastern Lincoln County, western Frontier County, and southern Hayes County, the depth to water exceeds 300 ft. However, throughout most of the study area, especially in Lincoln County, it ranges from 100 to 200 ft.

Throughout the study area, the unsaturated zone consists mostly of silt and clay (figs. 6-10). However, this unit primarily is silt or loess. In much of Lincoln and Hayes counties, this unsaturated silt is overlain by a thin mantle of sand and sandy soils. Water moves through the coarse-textured soils more readily to the underlying silts than it does through the finer textured soils elsewhere in the study area. In western Lincoln County, the unsaturated zone also includes sands, sandstones, gravels, and silts of the Ogallala Group. As the water table slopes towards the Republican Valley in Frontier and Hayes counties, greater thicknesses of Ogallala sediments, which are cemented with calcium carbonate, are included in the unsaturated zone. North of Hugh Butler Lake, the unsaturated zone is 200 ft thick; the upper half is

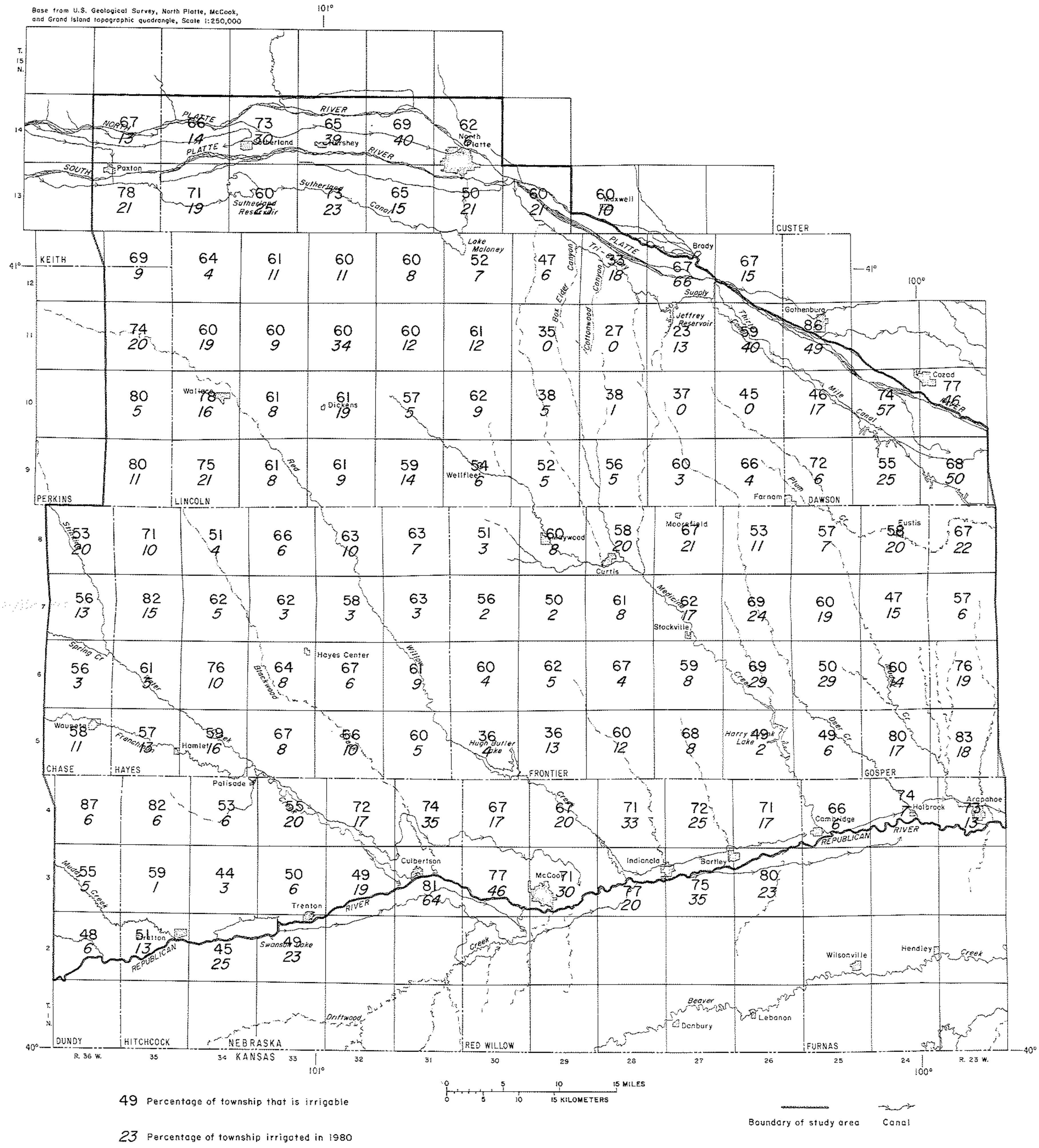


Fig. 15. Distribution of irrigable land and land irrigated in 1980.

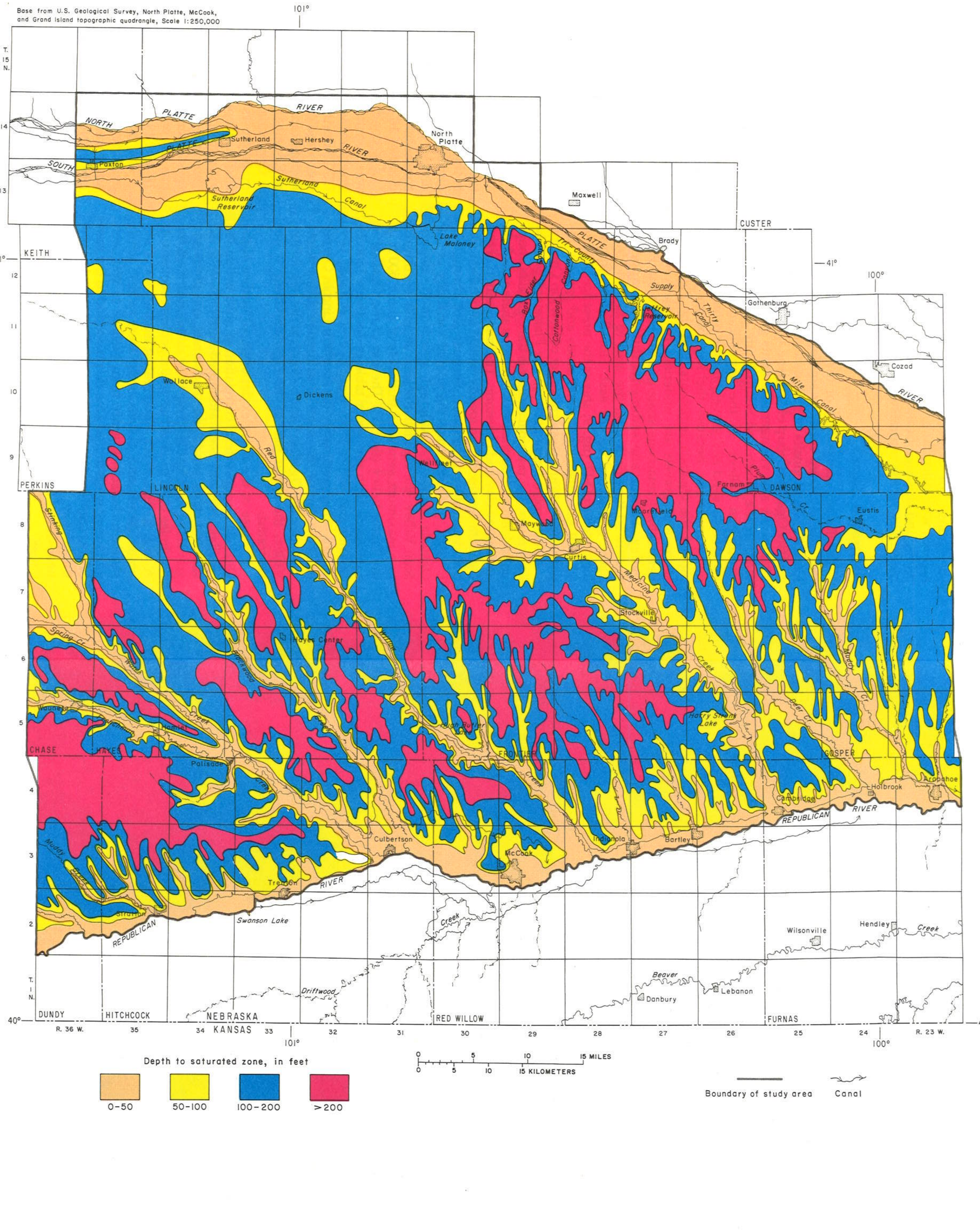


Fig. 16. Depth to saturated zone, 1977-1978.

composed of silt, and the lower half is composed of sands, gravels, sandstones, and siltstones of the Ogallala Group. The degree to which the Ogallala is cemented with calcium carbonate differs from place to place, and this significantly affects the rate of water movement to the saturated zone.

Saturated Zone

The fourth component of the hydrogeologic system, the saturated zone, or aquifer, consists of saturated alluvial deposits of Holocene to Pleistocene age and the Ogallala Group of Miocene age. The saturated Pleistocene and younger sediments generally are located in the North and South Platte and Platte and Republican valleys. In the Republican Valley, the Pleistocene sand and gravels are the principal source of groundwater because the Republican River removed the Ogallala sediments, and the Pleistocene sands and gravels are underlain by relatively impermeable Cretaceous shale and chalk. In the Platte Valley, Pleistocene sediments thin from approximately 60 ft at Paxton on the west to 20 ft at North Platte and Cozad on the east. However, hydrogeologic section D-D′ (fig. 9) shows the presence of 60 to 80 ft of saturated Pleistocene sands and gravels underlying the southwestern corner of Dawson County.

In the upland area between the Platte and Republican rivers, the principal aquifer is the Ogallala Group, underlain by impermeable Cretaceous shale and chalk or Tertiary clay and claystone. The composition of the Ogallala Group differs greatly within short distances both vertically and laterally. Sections A-A′ through E-E′ (figs. 6-10) illustrate the spatial variability of the Ogallala sediments. Although absent in the Republican Valley, the Ogallala thickens steadily northward to a maximum saturated thickness of about 500 ft in the Platte Valley (fig. 17). The top of the Ogallala is coincident with the water table in southern Lincoln County and slopes from west to east at about 11 ft per mi. At approximately the southern Lincoln County line, the top of the zone of saturation drops below the top of the Ogallala Group. South to the Republican Valley, the upper part of the Ogallala Group is unsaturated.

Because of the complex depositional history of the Ogallala Group, lateral correlation of units within the Ogallala has not been attempted. Instead, only the silts and clays, sands and sandstones, and sands and gravels of the Ogallala have been delineated from the test holes used to construct hydrogeologic sections A-A′ to E-E′ (figs. 6-10). The greatest thicknesses of saturated sands and gravels occur west to east across southern Lincoln County from Wallace to Wellfleet, and many wells in that area do not extend to the base of the aquifer. Aggregate saturated sand and gravel thicknesses in excess of 100 ft are common in the headwaters areas of Red Willow Creek and Medicine Creek.

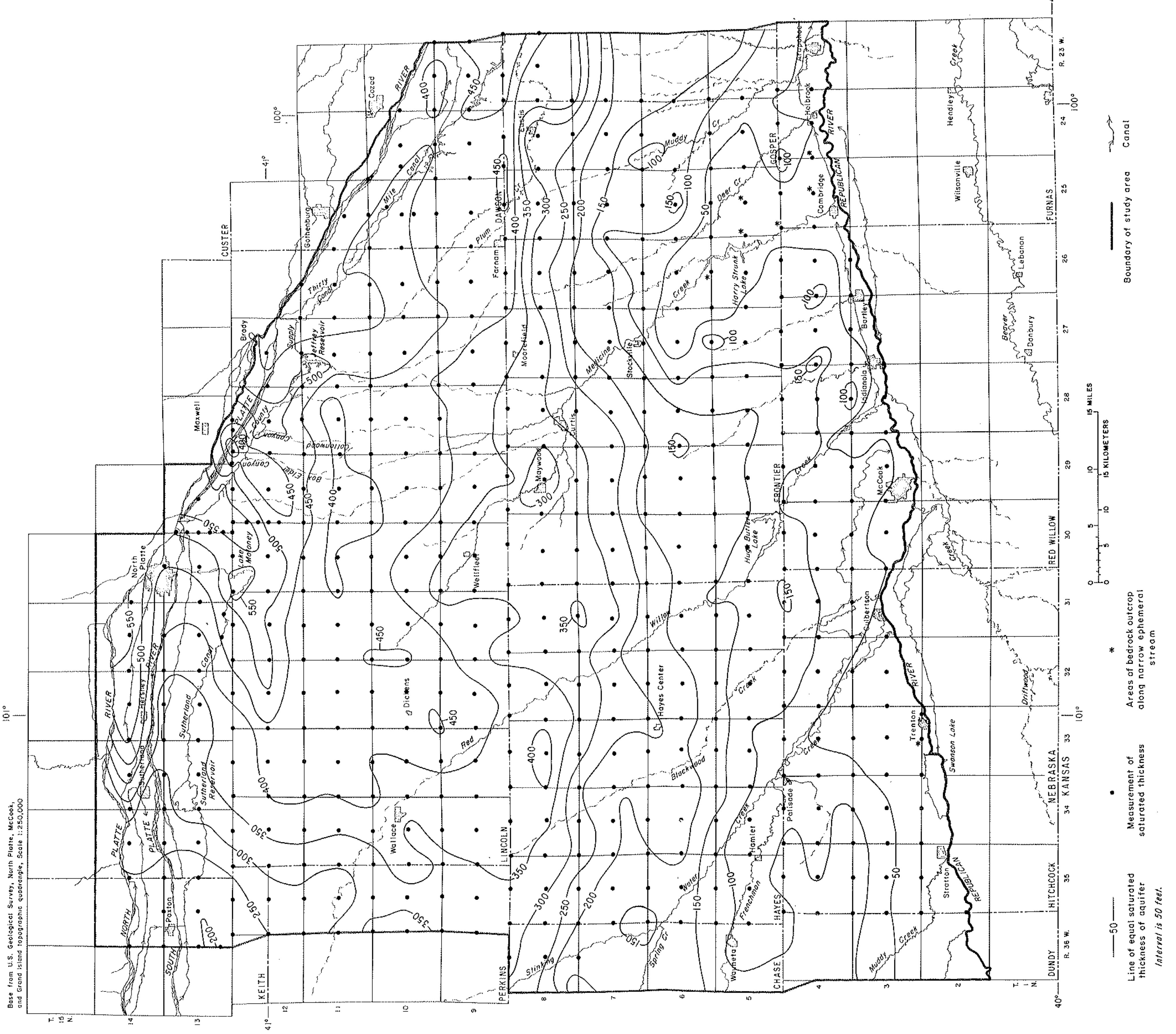
The Ogallala Group underlies virtually the entire area. It is missing only locally in the Republican River valley. Across southern Lincoln County, the Ogallala is saturated and of nearly uniform thickness (section D-D′, fig. 9). Although the Ogallala is continuous across Hayes and Frontier counties, its thickness and saturated thickness (fig. 17) differ greatly because of the incision of streams tributary to the Republican River (section E-E′, fig. 10). Generally, the saturated thickness of the aquifer thickens northward, from the area's south boundary except in the northwestern part of the study area where, in the 20 mi between Hershey and Paxton, the aquifer thins westward from about 450 ft to 225 ft.

With the initial delivery of water in 1935 to Sutherland Reservoir and Lake Maloney by the Sutherland Canal, seepage from these reservoirs and canals began to alter the balance between recharge and discharge from the aquifer. The installation of reservoirs on the Republican River, Red Willow Creek, and Medicine Creek from 1949 to 1962 and the growth of irrigation from wells during the 1960s and 1970s also altered predevelopment groundwater conditions. The approximate configuration of the top of the saturated zone before 1935 was constructed using records of water levels in early irrigation wells and altitudes along stream segments having perennial flow (fig. 18). Then, the groundwater divide between the Platte and Republican rivers roughly paralleled the Platte River and lay about 12 mi to the south. North of the divide from the western study-area boundary to the city of North Platte, groundwater movement was to the northeast at a gradient of approximately 10 ft per mi. East of the city of North Platte, where the Platte River turns to the southeast, groundwater movement north of the divide was eastward and southeastward. South of the divide, groundwater movement generally was to the southeast toward the Republican River valley at a gradient of 10 to 15 ft per mi.

A second water-table configuration map (fig. 19) was constructed by using approximately 450 water levels measured by the personnel of CSD and the USGS during the spring of 1977 and 1978. Water levels measured concurrently by the Twin Platte and Middle Republican NRDs, NPPD, CNPPID, and U.S. Bureau of Reclamation also were used.

Comparison of the two water-table configuration maps shows changes in direction of groundwater flow and a steepening of the water-table gradient in the vicinity of reservoirs and canals constructed between 1935 and 1978. Approximate differences between the two water-table configuration maps are shown in figure 20, which was developed by overlaying figures 18 and 19.

The most obvious water-level change is the rise extending across southern Lincoln County and into southwestern Dawson County. Westward from the city of North Platte, this rise is principally because of seepage from Sutherland Canal, Sutherland Reservoir, and Lake Maloney, but it is also partly because of the damming effect of that rise on the previously natural northeastward movement of groundwater toward the South Platte River. Water levels have risen


Base from U.S. Geological Survey, North Platte, McCook, and Grand Island topographic quadrangle, Scale 1:250,000
Line of equal saturated thickness of aquifer
Interval is 50 feet.
Measurement of saturated thickness
Areas of bedrock outcrop along narrow ephemeral stream
Boundary of study area
Canal
15 MILES
15 KILOMETERS
NEBRASKA
KANSAS
CUSTER
DAWSON
GOSPER
FURNAS
RED WILLOW
FRONTIER
HITCHCOCK
HAYES
DUNDY
CHASE
PERKINS
LINCOLN
KEITH
PLATTE RIVER
REPUBLICAN RIVER
North Platte
Maxwell
Brady
Gothenburg
Cozad
Curtis
Stockville
Maywood
Wellfleet
Hayes Center
Wallace
Dickens
Palisade
Hamlet
Wauneta
Trenton
Stratton
Culbertson
McCook
Indianola
Bartley
Cambridge
Holbrook
Arapahoe
Lebanon
Danbury
Wilsonville
Hendley
Farnam
Moorefield
Sutherland
Hershey
Paxton

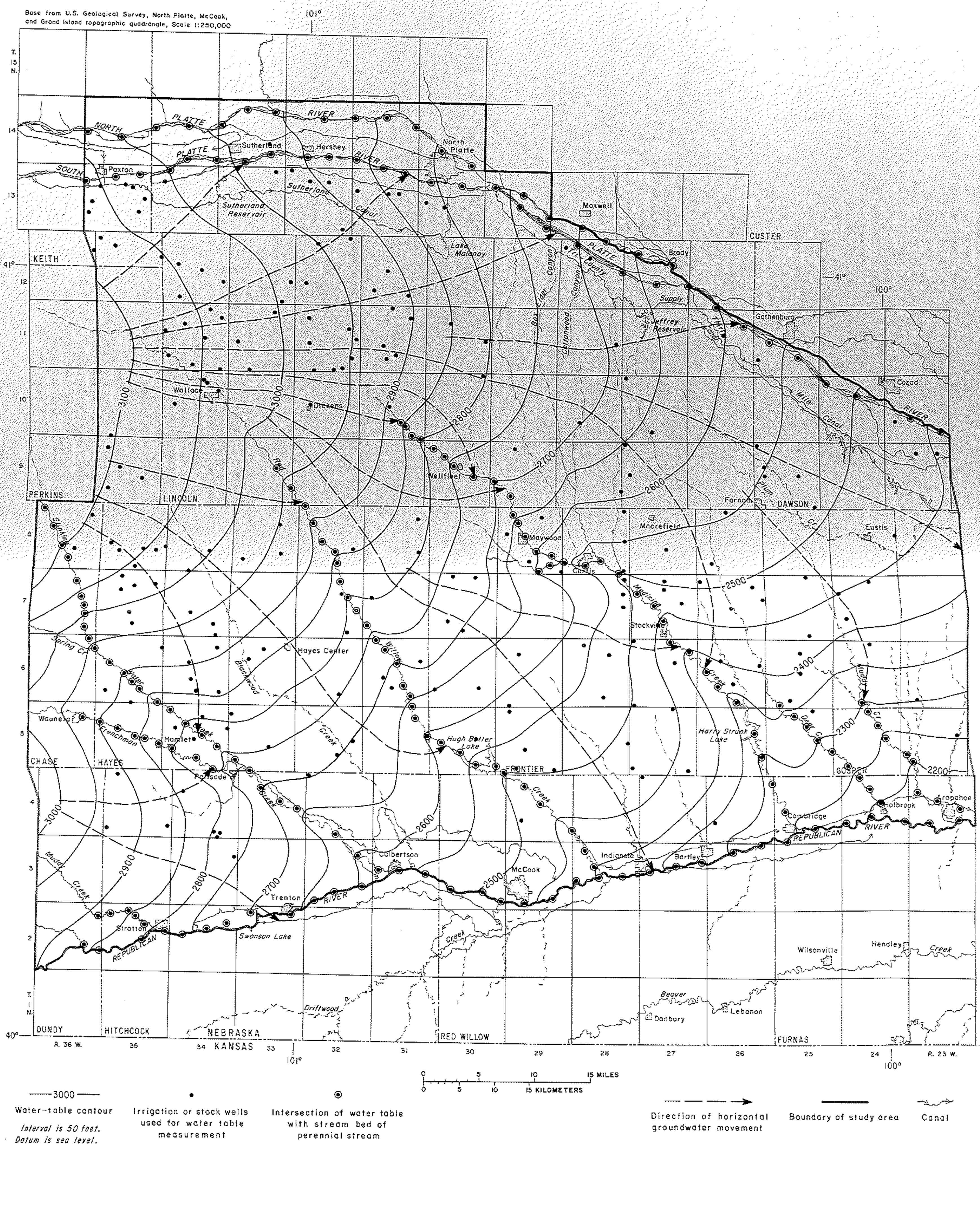


Fig. 18. Configuration of the water table before 1935.

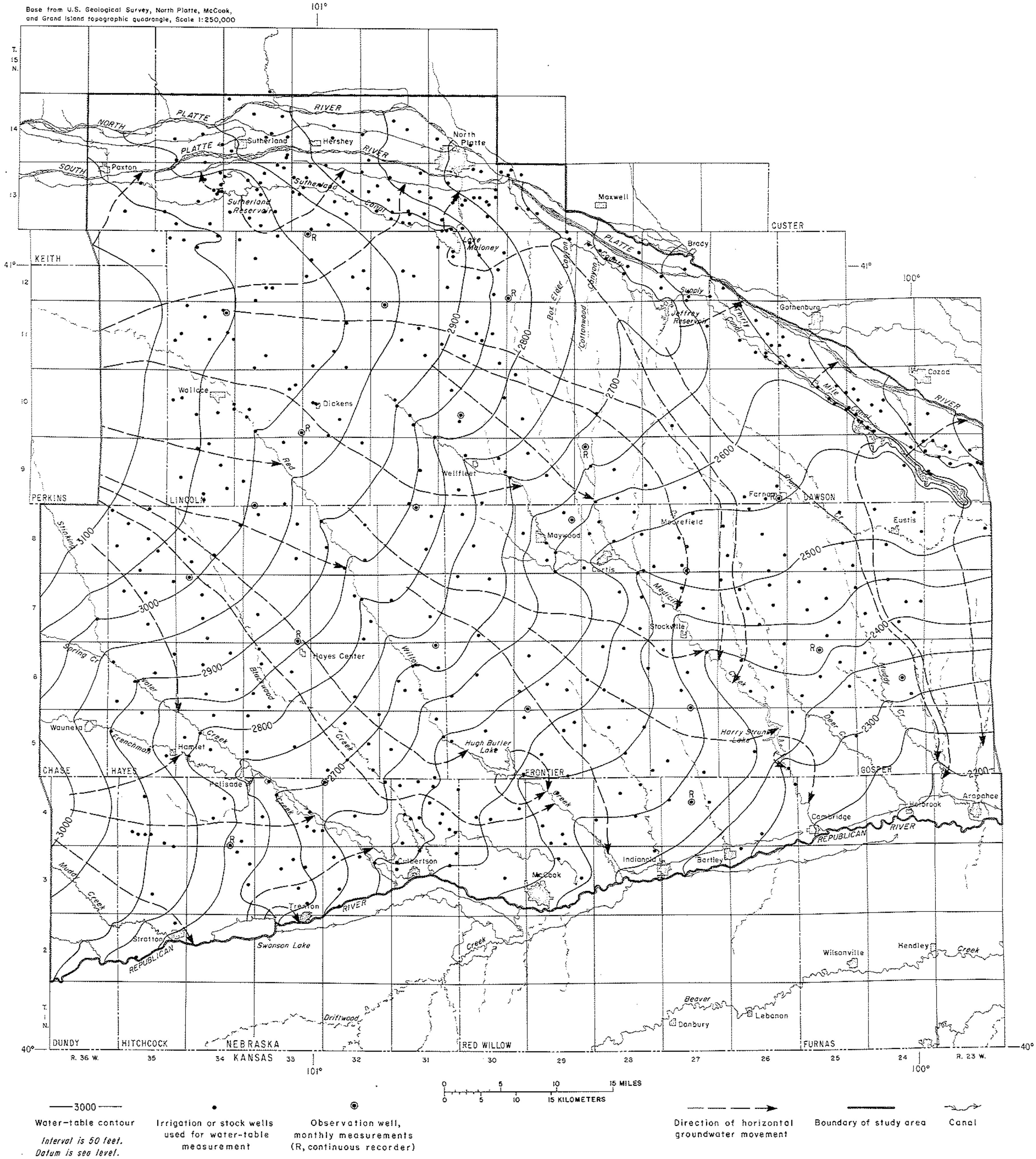


Fig. 19. Configuration of the water table, 1977-1978.

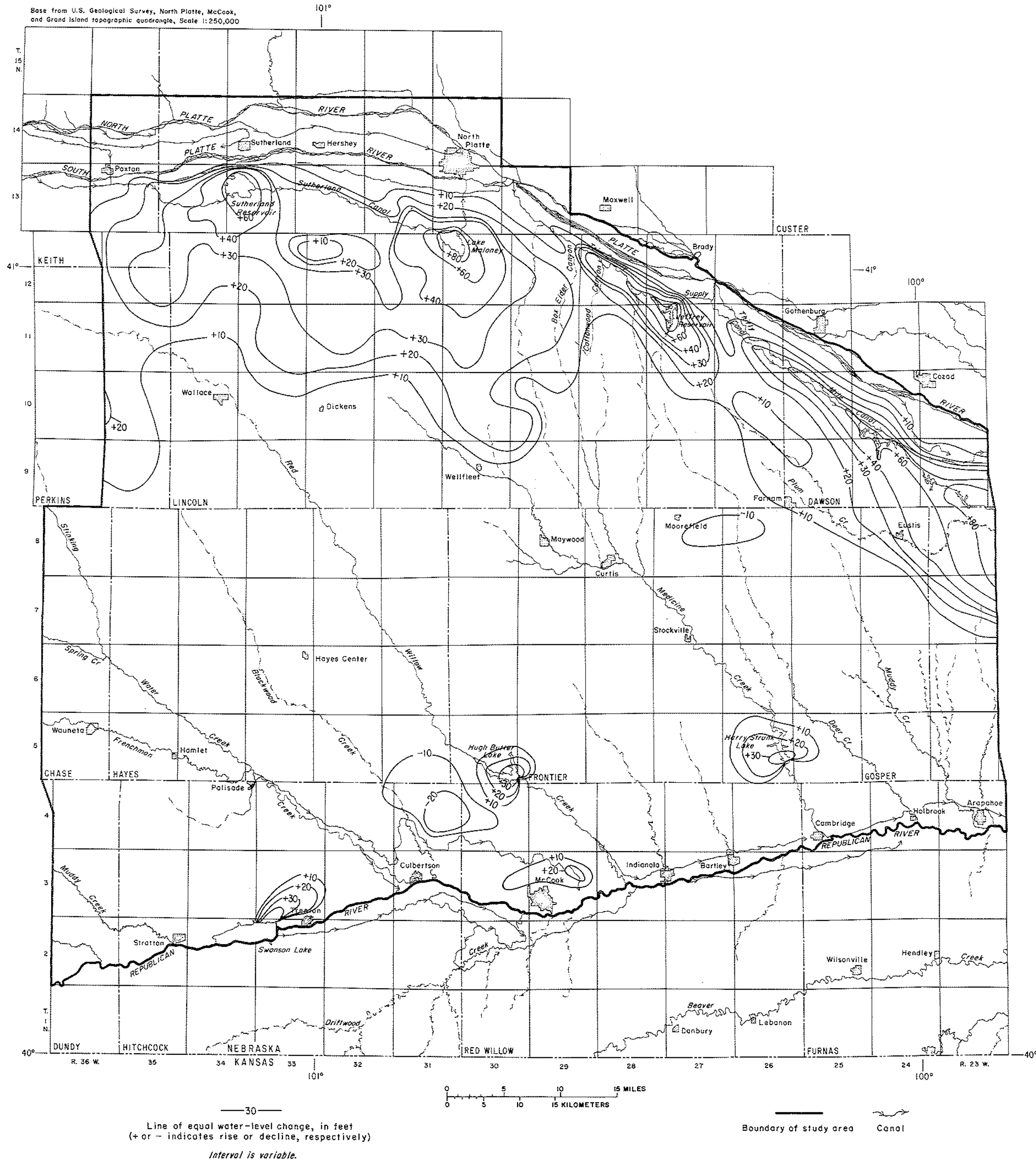


Fig. 20. Water-level changes from 1935-1978.

80 ft or more near Sutherland Reservoir and Lake Maloney.

Southeastward from the city of North Platte, the rise is because of seepage from the Tri-County Supply Canal and from Jeffrey Reservoir and other water-storage features along that canal. Because the rise is aligned with the predevelopment water-table divide, it does not have the same damming effect on the natural movement of water, but does greatly steepen the water-table gradient. The maximum rises in this area are 60 to 80 ft near Jeffrey Reservoir and near the lakes along the Tri-County Supply Canal south of the cities of Gothenburg and Cozad.

Water-table rises associated with seepage from Swanson, Hugh Butler, and Harry Strunk lakes generally are as much as 30 to 40 ft. However, outcrops of impermeable bedrock in the immediate vicinity of Swanson and Harry Strunk lakes make precise delineation of the rises difficult. Seepage from the Culbertson Extension Canal north of McCook has raised the water table 10 ft to a little more than 20 ft in an east-west-trending area about 8 mi long.

In only a few areas has the water table declined more than 10 ft. The largest area is northeast of Culbertson, mostly in northeastern Hitchcock County. Here the aquifer is only about 100 ft thick, and the current 1978 rate of withdrawal exceeds the aquifer's sustainable yield. Small areas in which the water table has declined less than 10 ft probably are scattered across the upland parts of Hayes and Frontier counties. One such area in eastern Frontier County is indicated by the progressive water-level decline since 1975 in the Orafino recorder well (fig. 21).

The Orafino well is one of 22 observation wells measured during this study to assess seasonal fluctuations of the water table. Except for it and the Indianola recorder well, all of the 20 other observation wells were drilled specifically for the study. At each observation well site a hole was drilled to the base of the aquifer and then cased with perforated casing from the water table to the bottom of the well. Of the 20 wells drilled for the study, nine were cased to the base of the aquifer; the others were cased to a lesser depth if caving had occurred in the lower part of the hole. During 1977 continuous recorders were installed on seven of the 20 new wells and also on the Indianola recorder well, which was drilled before this study. The Orafino well in southeastern Frontier County has been equipped with a continuous recorder since 1975. The locations of wells measured monthly and continuously are shown in figure 19. Hydrographs for the continuous recorder wells are presented in figure 21, and those for the wells measured monthly are presented in appendix A. Most of the wells showed some effects of seasonal pumping; some were negligible. The Dickens and Farnam wells showed the greatest seasonal fluctuation, 17 and 12 ft, respectively, from 1977 to 1981, but the water level in all wells returned to spring levels. Only the Orafino well showed a marked progressive water-level decline, dropping almost 4 ft from 1977 to 1981.

The base of the aquifer in the study area is considered to be the erosional surface cut into the Niobrara Formation or Pierre Shale, both of Late Cretaceous age, or the silt, siltstone, and clay of the Chadron or Brule formations of the White River Group of Tertiary (Oligocene) age. The Pierre Shale underlies the entire area except in a north-south band from Gothenburg to Cambridge, where post-Cretaceous and pre-Tertiary erosion removed the Pierre Shale and exposed the underlying Niobrara Formation (fig. 22). In most of southern Lincoln County, the Niobrara and Pierre are overlain by the much younger silt, siltstone, and clay of the Chadron or Brule formations. Because these bedrock formations are not considered to be important potential sources of water, their upper surface is regarded to be the lower drilling limit for irrigation wells.

To better define the base of the aquifer, 58 test holes were drilled during 1977 and 1978 to supplement earlier test holes drilled by CSD, USGS, and the U.S. Bureau of Reclamation (fig. 5). Logs of irrigation wells and oil wells also provided valuable subsurface information. Along the Republican River valley, contacts between the Ogallala and either the Niobrara or Pierre supplied additional control points.

A conspicuous feature of the bedrock surface or base of the aquifer is the buried valley that underlies the present Republican River valley. This trough probably was carved into Cretaceous bedrock in late Tertiary and/or early Pleistocene time and then was filled with a considerable thickness of sediment before it was re-excavated by erosion during late Pleistocene time. The Republican River may have deepened the valley somewhat before it deposited the alluvium on which it now flows. A similar buried valley at the base of the Ogallala Group underlies the present South Platte Valley from Paxton to North Platte. East of North Platte, where the current Platte River valley trends southeastward, a continuation of that buried valley trends northeastward. Also indicated is a prominent east-west ridge extending from northeastern Chase County to just south of Stockville in Frontier County. This ridge separates the two pre-Pleistocene valleys.

Water in Storage

Groundwater is stored in the pore spaces of the gravel, sand, sandstone, silt, and clay that constitute the aquifer in the study area. The amount of water in storage depends on the thickness of the aquifer and its total porosity. Saturated thickness varies in the study area from 0 to 10 ft along the Republican River to about 500 ft in the vicinity of North Platte. Using the total saturated thickness for the volume of the aquifer (fig. 17) and an estimate of 0.30 to 0.40 for total porosity (Lappala, 1978; Baver, 1956), the total water stored in the aquifer in the area during 1980 is estimated to have been between 225 and 300 million acre-ft.

However, only a part of the total water in storage

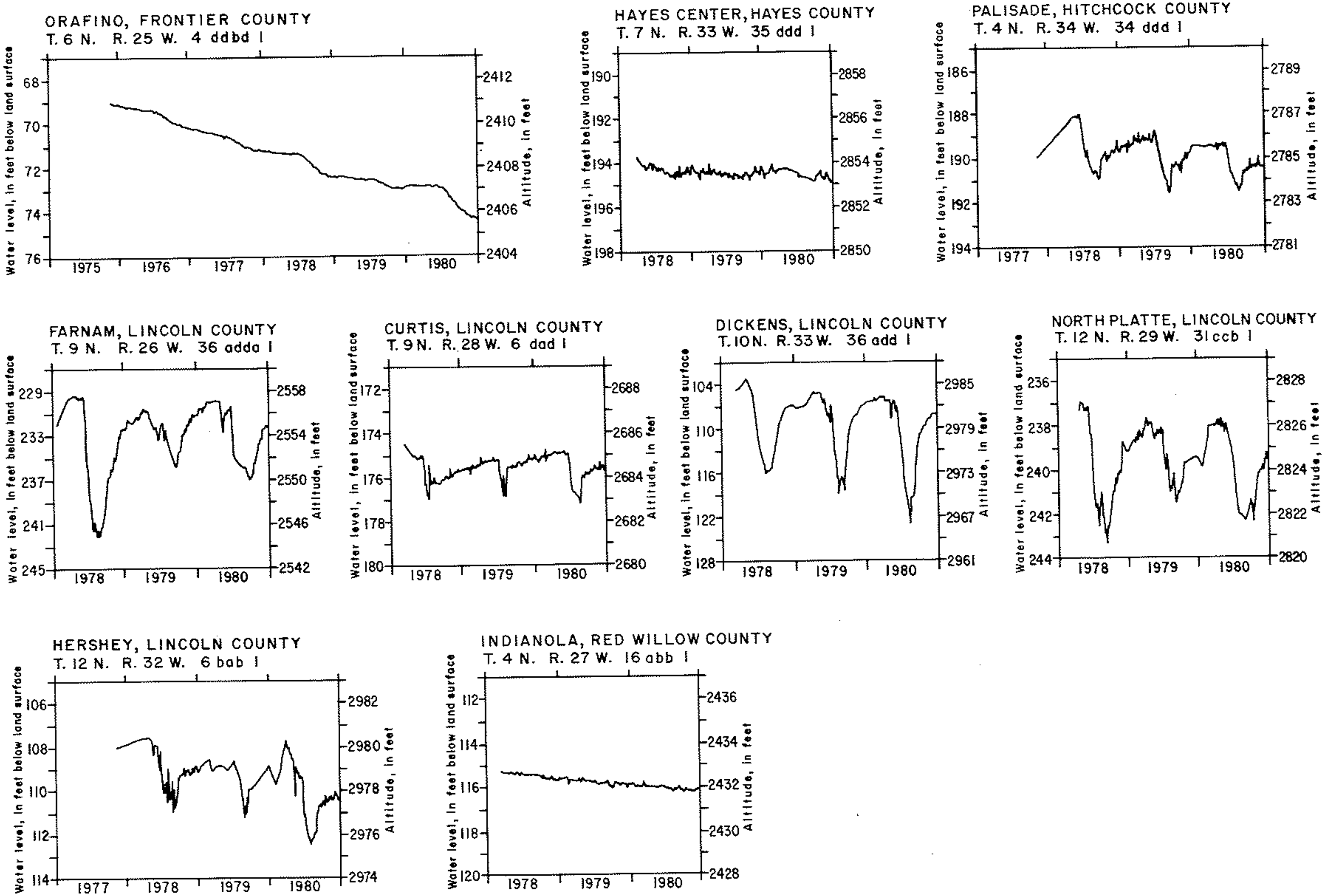


Fig. 21. Water levels in observation wells equipped with continuous recorders.

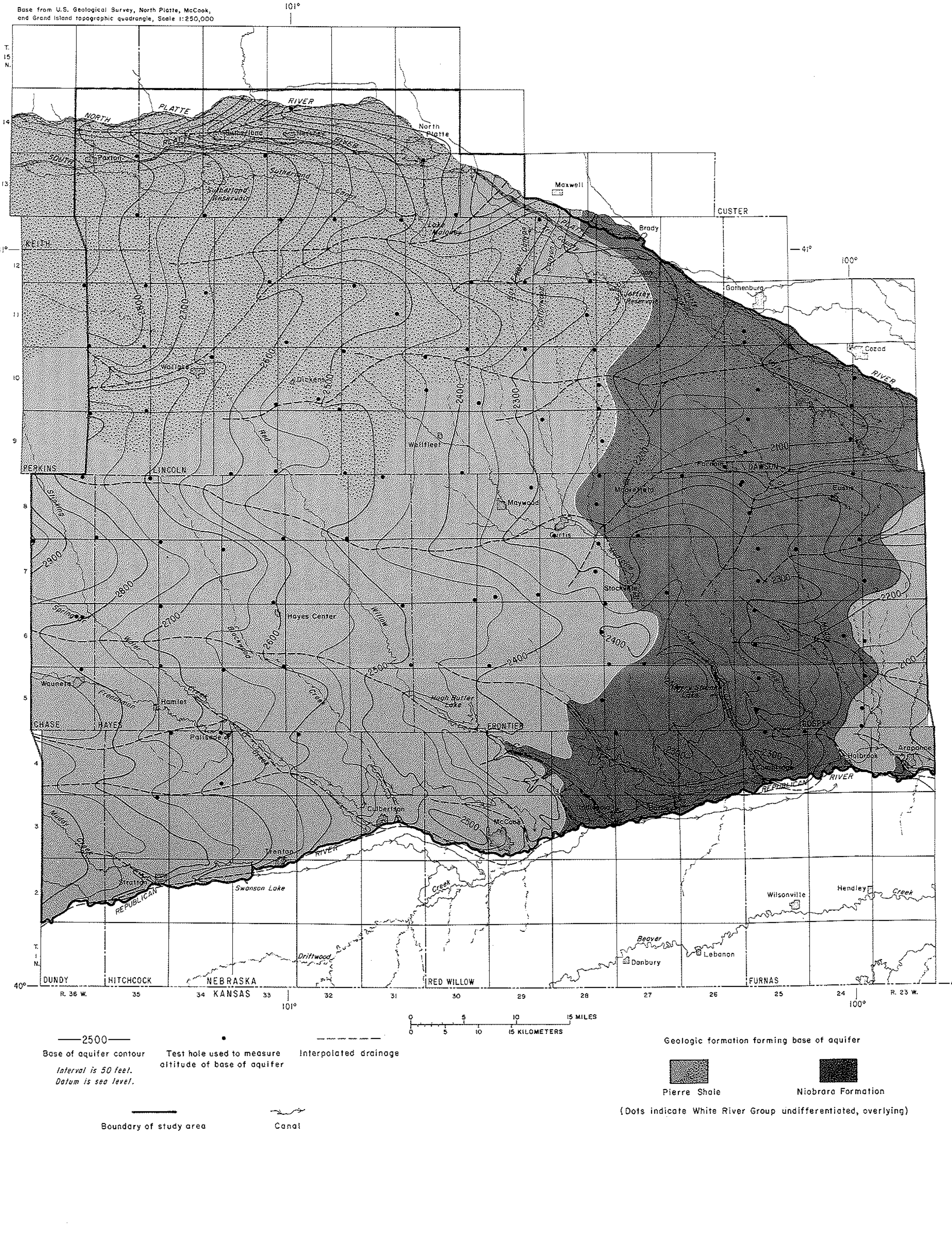


Fig. 22. Configuration of the base of the aquifer.

will drain from the aquifer under the influence of gravity. Specific yield is the amount of water available for extraction from the aquifer. Johnson (1967) estimated specific yield for sediments in the Ogallala Group as follows: 0.05 for siltstone, 0.10 for silt, 0.20 for sandstone, and 0.25 for sand and gravels. If the average specific yield is assumed to be 0.20, then approximately 150 million acre-ft of available groundwater is in storage in the study area.

Specific yield was estimated for each township by computing the average of the data values in a township or by using the nearest data value if there were no data for a particular township. The township specific-yield values for the study area are shown in figure 23.

Groundwater Movement

The rate of water movement within the saturated zone depends on the size, shape, and degree of interconnection of pore spaces and the hydraulic gradient. The term hydraulic conductivity is used to describe the rate at which a rock unit or saturated material will transmit water. The hydraulic conductivity of a saturated material is the rate (generally expressed in feet or meters per day) a unit volume of water will move in response to a unit hydraulic gradient through a cross section of unit area measured at right angles to the direction of flow (Lohman and others, 1972). Hydraulic-conductivity estimates based on laboratory analyses of hydraulic rotary-drill cuttings have been determined by CSD. Hydraulic-conductivity estimates for the different ranges of grain size that characterize the saturated zone in the study area are summarized in table 7.

Transmissivity is the rate at which water under the prevailing kinematic viscosity can be transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to the thickness-weighted sum of hydraulic conductivity across the saturated part of the aquifer perpendicular to the direction of flow (Lohman and others, 1972). Transmissivities for the area, in thousands of gallons per day per foot, are shown in figure 24. This map was derived by a combination of methods. Cuttings from all test holes in the area were analyzed and summarized. Hydraulic-conductivity estimates from table 7 were assigned to each lithology and multiplied by the thickness of each lithology in each test hole. The sum of transmissivity estimates for all of the lithologic intervals was plotted as the total transmissivity for each test hole. Transmissivity values also were estimated from drillers' summary logs as reported on irrigation-well registrations. In much of Lincoln County the transmissivity values determined from drillers' logs were conservative because many wells were not drilled to the base of the aquifer. Transmissivity values were estimated from irrigation-well registrations by dividing the reported yield by the reported drawdown and multiplying by 2,000 (after Logan, 1964).

Transmissivity values range from less than 20,000 gal per day per ft along the Republican Valley and in areas of Hayes and Frontier counties to more than 150,000 gal per day per ft in Lincoln County. Generally, estimated transmissivity increases as the saturated zone thickens from south to north. Across northeastern Hitchcock and northwestern Red Willow counties, the thin saturated zone contains a large percentage of gravel, shown as a zone of high transmissivity. Bedrock highs in south-central Hayes County and in west-central and southeastern Frontier County apparently diverted any deposition of coarse materials, producing a very fine-grained saturated zone and low transmissivities. The low transmissivity values along the Republican River valley reflect a very thin, although in some places a coarse-grained, saturated zone.

The direction of groundwater movement generally is from west to east across the area as indicated by flow paths on figure 19. Hydraulic gradients generally are 10 to 15 ft per mi. Average velocities in the study area probably range from less than 50 ft per yr to more than 200 ft per yr.

Quality of Water

Dissolved chemical constitutents in water are important because the amounts and combinations of dissolved ions in solution determine the water's suitability for most uses. Generally, water that has low concentrations of dissolved solid is considered to be of "good" quality; whereas, highly mineralized water is considered to be of "poor" quality. However, this is an arbitrary designation that depends upon the use of the water. For example, water that is of "good" quality for irrigation in one area may be of "poor" quality in another area because of differences in soil and subsoil characteristics.

Dissolved-solids concentrations of water in consolidated aquifers depend upon the hydrologic and geologic environments of the aquifers and upon physical and chemical processes acting upon these environments. Precipitation ordinarily contains only trace amounts of dissolved solids and gases. As precipitation percolates into the ground, it dissolves or reacts with minerals and organic matter in soils and subsoils. The constituents available for solution in soils and subsoils may be derived from the geologic processes of weathering or deposition; from processes such as the fixation of atmospheric nitrogen in the soil; from biochemical processes related to the life cycle of plants, humans, or animals; or from a variety of other processes, both natural and anthropogenic. The precipitation containing the material dissolved from soils and subsoils that moves into the aquifer helps determine the overall chemical composition of water in the aquifer. Solution of materials in the aquifer and movement of water of different compositions from underlying deposits into the aquifer also influence the chemical composition of water in the aquifer.

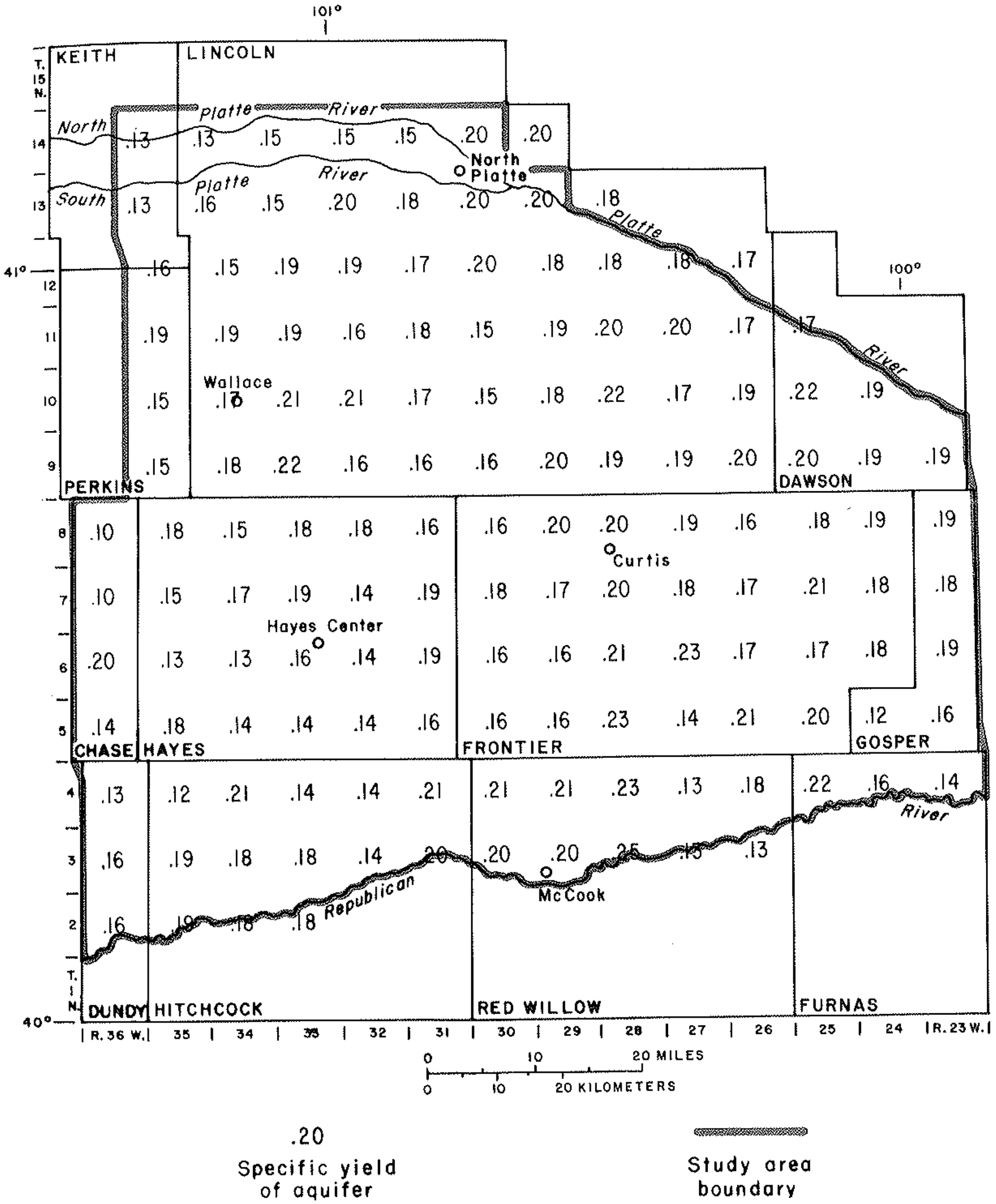


Fig. 23. Average specific yield of the aquifer for each township.

Table 7. Hydraulic conductivities estimated from descriptions of saturated sediments comprising a lithologic unit

Grain-size class or range (from description of saturated sediments)	Hydraulic conductivity, in feet per day[a] — Degree of sorting: Poor	Moderate	Well	Silt content: Slight	Moderate	High
Clay and silt:						
Clay	------	------	------	1.0	------	------
Silt, slightly clayey	------	------	------	10.0	------	------
Silt, moderately clayey	------	------	------	8.0	------	------
Silt, very clayey	------	------	------	4.0	------	------
Silt; loess; sandy silt	------	------	------	15.0	------	------
Sand and gravel[b]:						
Very fine sand	13	20	27	23	19	13
Very fine to fine sand	27	27	------	24	20	13
Very fine to medium sand	36	41-47	------	32	27	21
Very fine to coarse sand	48	------	------	40	31	24
Very fine to very coarse sand	59	------	------	51	40	29
Very fine sand to fine gravel	76	------	------	67	52	38
Very fine sand to medium gravel	99	------	------	80	66	49
Very fine sand to coarse gravel	128	------	------	107	86	64
Fine sand	27	40	53	33	27	20
Fine to medium sand	53	67	------	48	39	30
Fine to coarse sand	57	67-72	------	53	43	32
Fine to very coarse sand	70	------	------	60	47	35
Fine sand to fine gravel	88	------	------	74	59	44
Fine sand to medium gravel	114	------	------	94	75	57
Fine sand to coarse gravel	145	------	------	107	87	72
Medium sand	67	80	94	64	51	40
Medium to coarse sand	74	94	------	72	57	42
Medium to very coarse sand	84	98-111	------	71	61	49
Medium sand to fine gravel	103	------	------	84	68	52
Medium sand to medium gravel	131	------	------	114	82	66
Medium sand to coarse gravel	164	------	------	134	108	82
Coarse sand	80	107	134	94	74	53
Coarse to very coarse sand	94	134	------	94	75	57
Coarse sand to fine gravel	116	136-156	------	107	88	68
Coarse sand to medium gravel	147	------	------	114	94	74
Coarse sand to coarse gravel	184	------	------	134	100	92
Very coarse sand	107	147	187	114	94	74
Very coarse sand to fine gravel	134	214	------	120	104	87
Very coarse sand to medium gravel	170	199-277	------	147	123	99
Very coarse sand to coarse gravel	207	------	------	160	132	104
Fine gravel	160	214	267	227	140	107
Fine to medium gravel	201	334	------	201	167	134
Fine to coarse gravel	245	289-334	------	234	189	144
Medium gravel	241	321	401	241	201	160
Medium to coarse gravel	294	468	------	294	243	191
Coarse gravel	334	468	602	334	284	234

[a] Hydraulic conductivity values are from an unpublished and undated paper by E.C. Reed and R. Piskin, Conservation and Survey Division, University of Nebraska.
[b] Reduce hydraulic conductivity by 10 percent if grains are subangular.

Concentrations of constituents in water within the aquifer are related to both their availability in the soil or subsoil and the solubility of the individual constituents. Some constitutents such as sodium and chloride are extremely soluble, whereas concentrations of calcium and magnesium may be controlled by their solubilities of carbonate or by ion-exchange reactions that occur on the surfaces of clay particles in the saturated and unsaturated zones. Concentrations of other constituents may be controlled by oxidation-reduction, precipitation, temperature-related reactions, or biochemical processes.

Sampling History

The quality of groundwater in the study area was first analyzed by the USGS in 1936, when five samples, two from Lincoln County and one each from Hayes, Hitchcock, and Red Willow counties, were collected from domestic and stock wells. Between 1936

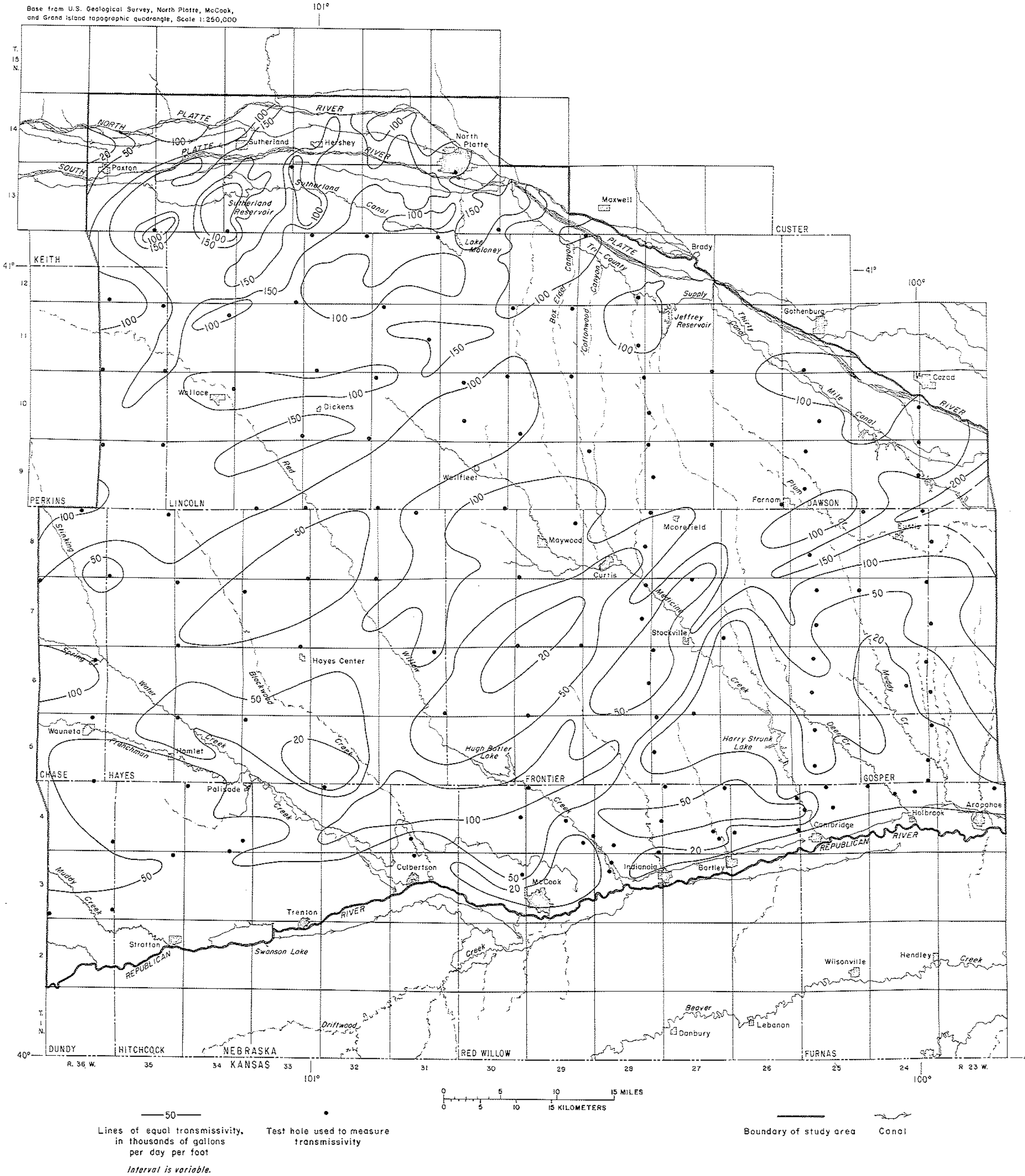


Fig. 24. Transmissivity of the aquifer.

and 1958, 15 more samples were collected by USGS personnel, principally from public-supply wells. From 1958 until 1977, no samples were collected from wells in the study area.

Water-quality studies on the Twin Platte-Middle Republican area began in 1977 and 1978 with the installation of observation wells for continuous recording of water levels. Following casing, installation, and development, water samples were collected from these wells. A total of seven observation wells in the study area were sampled during 1977 and 13 during 1978.

Water-quality samples were collected from 99 irrigation wells in the study area during the summer of 1979. Eighty-three of the wells were sampled once, and 16 were sampled twice, once at the beginning of the irrigation season and once at the end. A summary by county of the water-quality sampling history of wells in the study area is listed in table 8.

Table 8. Water sampling history by county

County	Total wells sampled		Samples collected (1977-79)				Wells sampled twice in 1979
	Pre-1977	1977-79	1977	1978	1979	Total	
Frontier	4	31	4	1	30	35	4
Hayes	4	23	0	4	24	27	4
Hitchcock	5	15	2	0	15	17	2
Lincoln	4	41	1	8	37	46	5
Red Willow	3	8	0	0	9	9	1
Totals	20	118	7	13	115	134	16

Chemical Composition and Variations

The Ogallala Group is the probable source of water for all samples collected from 1977 to 1979. The following discussion is based only on results of analyses of samples collected during this period in the study area. Irrigation-well samples collected during 1979 were on the basis of approximately one well per township. Locations of wells were determined based on irrigation-well registration information. When scheduled wells were not available for sampling, an alternate well, as close to the predetermined location as possible, was sampled. Information regarding the construction and completion of the alternate well was obtained from the land owner or tenant.

All samples were collected using USGS sampling methods and techniques. Water temperature, pH, and specific conductance were measured when each sample was collected. Other constituents were measured at the USGS Central Laboratory, Arvada, Colorado. Seventeen constituents or properties were measured on all samples. Results of the analyses of these constituents or properties are listed in USGS Annual Reports for water years 1977, 1978, and 1979 (U.S. Geological Survey, 1978-1980).

Descriptive statistics and duration tables for 13 constituents or properties measured from 1977 to 1979 are given in table 9. For those wells from which two samples were collected during 1979, the statistical table includes only the values from the second sample

Table 9. Summary of groundwater quality data, 1977-1979, Twin Platte-Middle Republican study area

[μS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter]

Water-quality constituent or property	Sample size	Descriptive statistics				Values of samples less than or equal to percentages shown				
		Maximum	Minimum	Mean	Standard deviation	10%	25%	50%	75%	90%
Specific conductance (μS/cm)	116	1190	276.0	460	137	341	373	417	502	616
Alkalinity (mg/L as $CaCO_3$)	117	350	130.0	193	43	150	160	180	210	250
Calcium, dissolved (mg/L as Ca)	118	150	34.0	56	18	41	44	51	66	74
Magnesium, dissolved (mg/L as Mg)	118	40	5.7	15	4.8	9	11	15	17	20
Sodium, dissolved (mg/L as Na)	118	76	4.0	17	13	8.7	9.8	12	18	27
Potassium, dissolved (mg/L as K)	118	22	8.2	11	1.9	9.3	10	11	12	13
Chloride, dissolved (mg/L as Cl)	117	28	1.2	5.8	6.2	1.8	2.4	3.4	5.5	13
Sulfate, dissolved (mg/L as SO_4)	117	330	4.0	33	49	12	16	19	22	52
Fluoride, dissolved (mg/L as F)	117	1.2	0.3	0.7	0.2	0.4	0.5	0.6	0.8	1
Silica, dissolved (mg/L as SiO_2)	117	72	33.0	60	67	54	58	61	65	67
Nitrogen, NO_2 + NO_3, dissolved (mg/L as N)	117	20	0.12	3.0	2.2	1.5	2	2.6	3.4	4
Boron, dissolved (μg/L as B)	118	350	30.0	77	37	50	60	70	80	100
Solids, sum of dissolved constituents, (mg/L)	117	875	215.0	329	95	252	272	302	350	444

collected from each well. Although maximum and minimum concentrations define the overall range of occurrence of the constituents, the 90th and 10th percentiles in the duration tables generally define a more effective range for examination of groundwater quality. Constituent values greater than the 90th percentile or less than the 10th percentile are outliers that may represent extraordinary events or situations, or occasionally may indicate random errors in the data base. While it is extremely important to understand the significance of individual outliers for projects or users in specific areas, they are less important for general knowledge of the quality of water in the aquifer. The median (50th percentile) may provide better information about the average constituent concentrations than does the mean. The mean may be unduly affected by the outliers, whereas the median is not. This can be illustrated by the statistics for specific conductance. These values range from 276 to 1,190 microsiemens per centimeter (μS/cm) at 25° Celsius. The mean of 460 μS/cm is 10 percent greater than the median of 417 μS/cm. This would indicate that the mean is affected by the few samples that had specific conductance values significantly greater than the 90th percentile. The 90th percentile is 616 μS/cm, a difference of 574 μS/cm from the maximum. On the other hand, the 10th percentile value of 341 μS/cm is only 65 μS/cm greater than the minimum observed value.

Concentrations of principal cations and principal anions in milligrams per liter (mg/L) are compared in figure 25. These box plots show maximum, minimum, mean, median, and 75th and 25th percentiles for each constituent. They clearly indicate that for the entire study area, calcium is the principal cation and alkalinity, which provides an estimate of carbonate and bicarbonate, represents the principal anions.

Calcium, carbonate, and bicarbonate are derived from the soil from unsaturated fluvial and eolian Quaternary deposits overlying the Ogallala Group, and from the solution of calcareous material in the Ogallala Group. Silica also is an important constituent in the groundwater. Quaternary sands and gravels, especially dune sands, are a source of silica. Ninety percent of the observed silica concentrations exceed 54 mg/L; the median silica concentration is 61 mg/L.

In a few analyses where specific conductance values exceed 750 μS/cm, other constituents, notably sodium and sulfate, are detected in quantities approaching those of calcium and bicarbonate. These analyses are from wells near the South Platte River, the Tri-County Supply Canal, and the Republican River. In these areas, the native groundwater has been replaced by, or is affected by, seepage from the rivers or canals or is affected by seepage of highly mineralized water from bedrock.

Data indicate that a direct relation exists between specific conductance and dissolved-solids concentrations. Dissolved-solids concentrations were plotted against specific conductance values for 116 samples (fig. 26). The line of best fit indicates that dissolved-solids concentrations in milligrams per liter are 0.72 times specific-conductance values. This means that dissolved-solids concentrations in milligrams per liter may be estimated reliably from specific-conductance values by multiplying the specific-conductance value by 0.72. Because specific conductance may be measured quickly and easily in the field, reliable estimates of dissolved solids for other sites in the study area may be obtained rapidly by use of this method.

Specific-conductance values for 118 wells are plotted on figure 27, and lines of equal specific conductance are derived from these values. Elevated specific-conductance values south of the South Platte and Platte rivers and on either side of the Tri-County Supply Canal are related to enrichment or replacement of the native groundwater by seepage of more highly mineralized water into the aquifer from these rivers and canals. These areas correspond roughly with water-level rises in the same general locations.

Specific-conductance values show approximately a 40 percent increase from west to east across the study area in the uplands between the South Platte River and Platte River valleys to the north, and the Republican River valley to the south. The increase in specific conductance primarily is the result of increased calcium concentrations and alkalinity values; calcium and alkalinity are 40 to 60 percent greater in groundwater in the eastern part of the study area. An exception is in groundwater beneath a small area of sandhills south of Lake Maloney in Lincoln County. Specific-conductance values of less than 300 μS/cm are detected in this area. Other exceptions, such as well no. 6N-29W-32ccc in Frontier County and well no. 6N-31W-1bbb in Hayes County, probably are related to a localized source of more highly mineralized water in the immediate vicinity of the well (with 6N-31W-1bbb) or to incomplete development of an observation well before sample collection (with 6N-29W-32ccc).

The increase of mineralization in groundwater from west to east in the study area does not appear to be related to well depth, depth to water, saturated thickness of the aquifer, climatic conditions, or availability of soluble material in the soils and subsoils. The regional flow system of the Ogallala moves water from west to east through the study area; discharge areas are to the east of the Twin Platte-Middle Republican study area. Additional calcareous material is probably dissolved from the deposits comprising the aquifer, thus increasing mineralization of the water as it moves through the study area.

Water-quality Changes During the 1979 Irrigation Season

As previously mentioned, 16 of the irrigation wells were sampled twice during 1979. The first samples were collected from each well immediately before or just after the onset of irrigation. The second samples

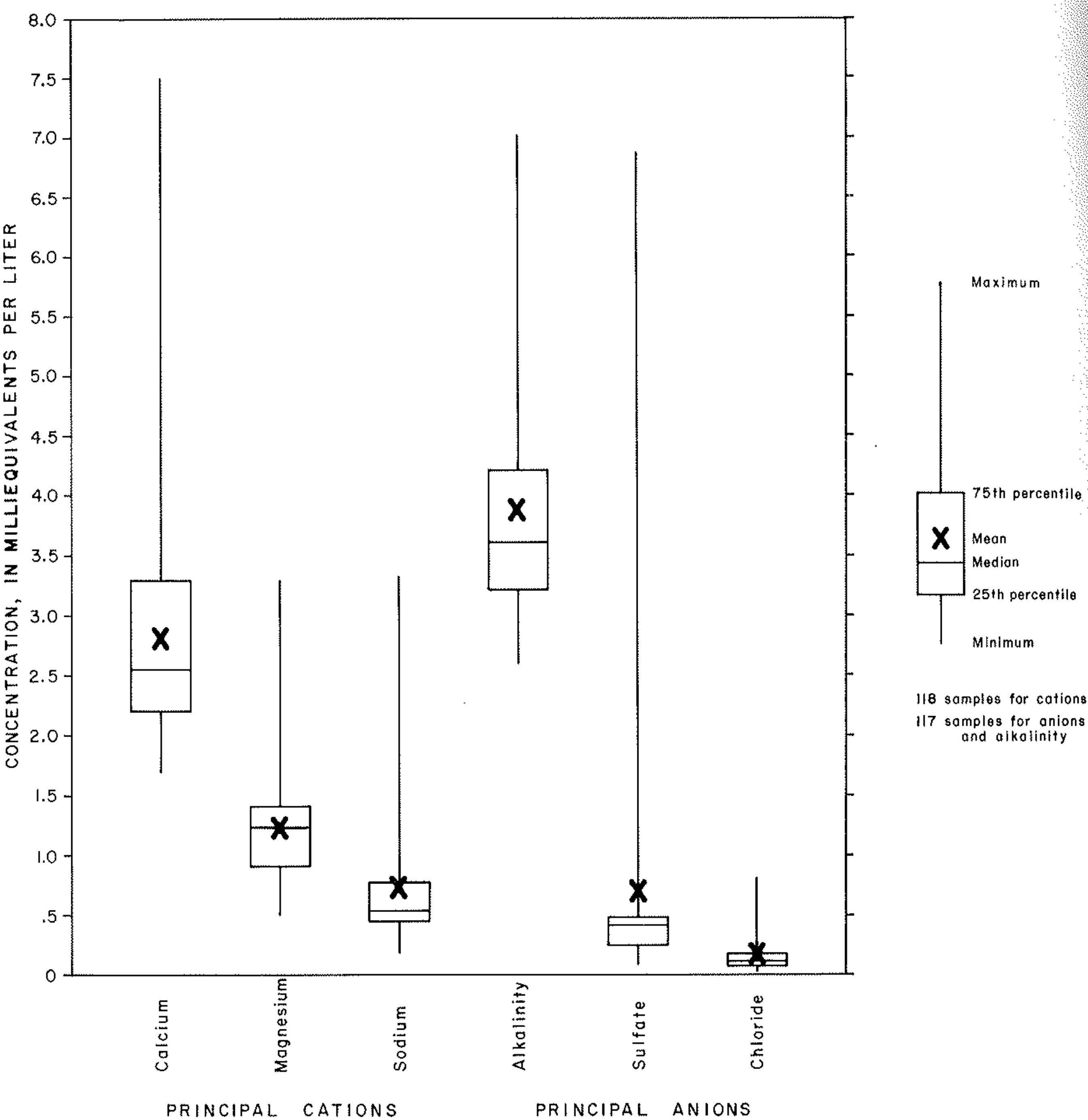


Fig. 25. Distribution of concentrations of principal cations, anions and alkalinity in groundwater.

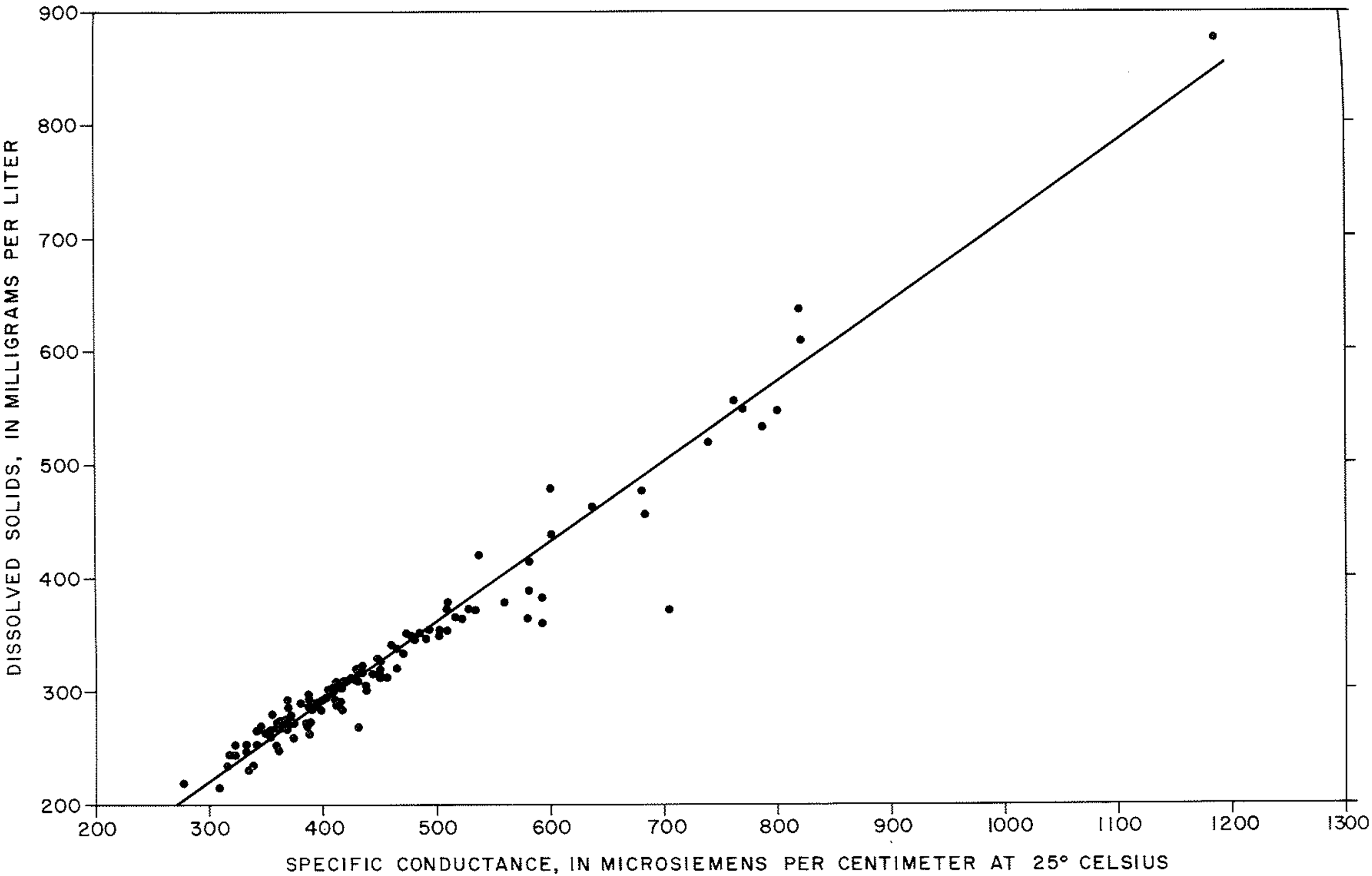


Fig. 26. Relation of concentration of dissolved solids to specific conductance.

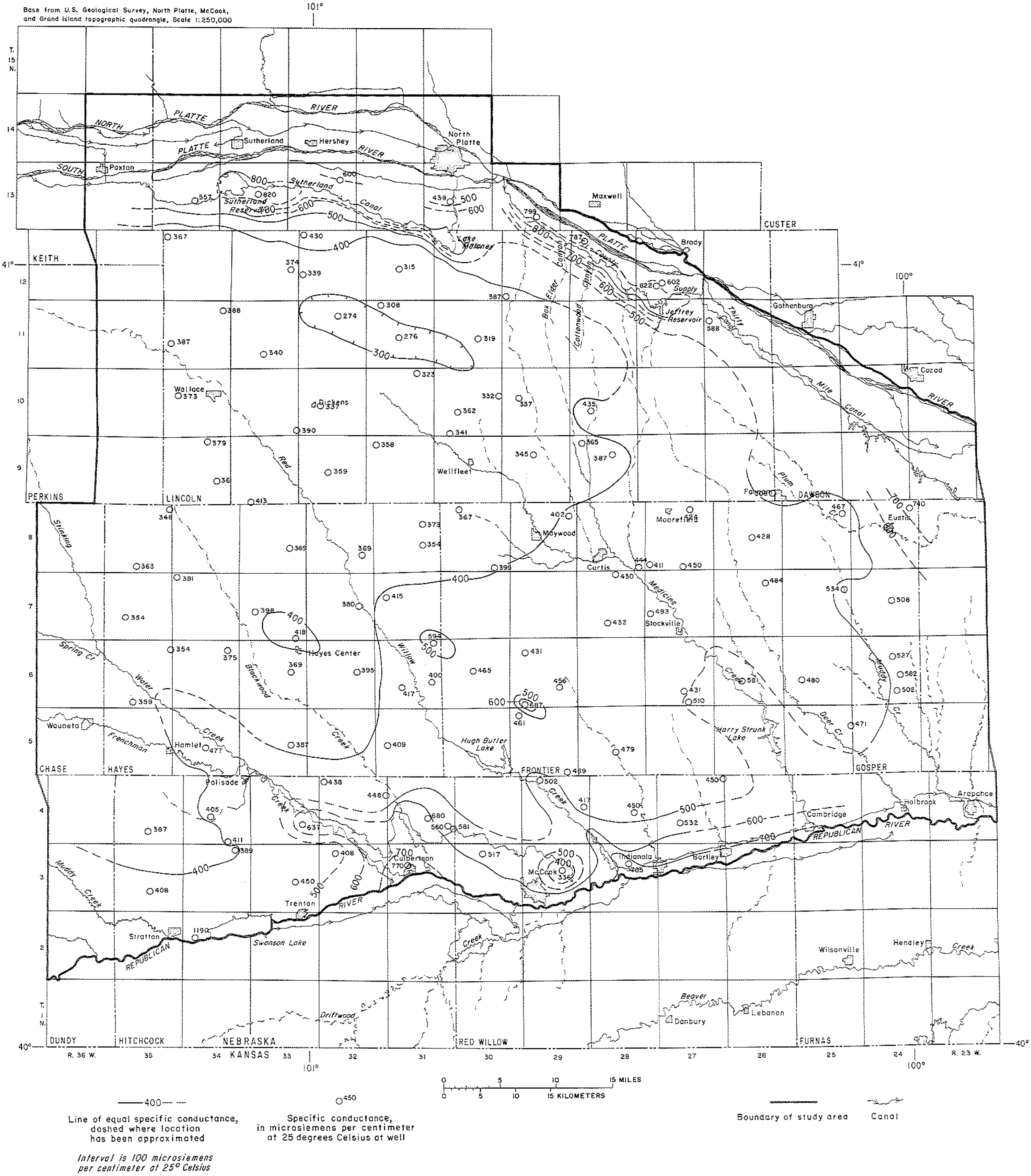


Fig. 27. Specific conductance of water from wells sampled from 1977 to 1979 and lines of equal specific conductance.

were collected at or near the end of the irrigation season, after the wells had been pumped for long periods. Two samples were collected from each of the wells to determine whether extended pumping is accompanied by changes in the quality of groundwater in the study area.

Results of the repetitive sampling for the 16 wells are summarized as follows:

Wells with no change	Increased mineralization				
	Wells with change	Percent of standard deviation (137.0)			Maximum percent change
		0-49	50-100	>100	
4	5	3	1	1	61.9

Decreased mineralization				
Wells with change	Percent of standard deviation (137.0)			Maximum percent change
	0-49	50-100	>100	
7	6	0	1	29.1

Changes are determined on the basis of increased or decreased specific-conductance values between the first and second samples. If specific-conductance values changed by more than one standard deviation (greater than 100 percent of standard deviation), the change is considered significant. Mineralization increased by greater than one standard deviation in water from one well and decreased by greater than one standard deviation in water from another.

One well in which increased mineralization greater than one standard deviation occurred is located near an irrigation canal. This well, no. 8N-24W-1cb in Frontier County, is located approximately 3 mi from the Tri-County Supply Canal (fig. 27). During the irrigation season, the drawdown cones created by the pumping appear to induce the movement of more highly mineralized water derived from canal seepage into this well. This is not unexpected, because concentrations of sodium, chloride, and sulfate are much larger in water from the Platte River than in the native groundwater of the study area. Specific-conductance values and concentrations of sodium, chloride, and sulfate are shown below for this well:

Table 10. Specific-conductance values and concentrations of sodium, chloride, and sulfate for well no. 8N-24W-1cb

Sample period	Specific conductance		Sodium (mg/L)	Chloride (mg/L)	Sulfate (mg/L)
	(µS/cm at 25° C)	Percent increase			
Before irrigation	457	—	19	4.2	21
After irrigation	740	61.9	49	21	150

The other well in which a significant change occurred is located in Hitchcock County. Specific conductance values of water from this well, no. 4N-31W-25bc (fig. 27), changed from 723 to 560 µS/cm at 25° C, a decrease of 29.1 percent. Reasons for this change are unknown.

Suitability for Use

Water is considered suitable if it can be used safely for human and animal consumption or other domestic uses, or if it can be used for crop watering without harm to the crops to which it is applied. Drinking-water criteria or standards established by the U.S. Environmental Protection Agency (EPA) (U.S. Congress, 1988) provide guidelines for suitability of drinking water. Guidelines for irrigation suitability are contained in U.S. Department of Agriculture Handbook 60 (U.S. Department of Agriculture, 1954).

Drinking Water Suitability

Maximum contaminant levels (MCL) for drinking water established by EPA are applicable to all community water systems. Those for nitrate (as nitrogen) also are applicable to non-community water systems. MCLs for constituents measured on samples from the study area are flouride, 4 mg/L, and nitrate as nitrogen (N), 10 mg/L (Code of Federal Regulations, 1988). The USGS regularly measures nitrite plus nitrate as N in water samples. These measurements are roughly equivalent to measurements for nitrate as N alone and will be referred to as "nitrate as N" in the discussion that follows. Nitrite is an unstable ion that generally is detected only in very small quantities in natural water. All species of nitrogen, nitrate, nitrite, or ammonia in water are derived from human or animal waste, plants, nitrogen fixation in soils, or other external sources such as fertilizer or lightning. Generally, they are not derived from geologic sources.

Fluoride concentrations were measured for water samples from 117 wells collected from 1977 to 1979. Concentrations of flouride, a constitutent that occurs naturally in water, were below the MCL in all samples.

Nitrate as N concentrations for 117 wells are plotted in figure 28. Concentrations exceeded the MCL in only two wells, 11 mg/L in well no. 6N-31W-1bbb in Hayes County, and 20 mg/L in well no. 4N-33W-26bb in Hitchcock County. Both concentrations apparently were related to point-source contamination or, in the case of the Hayes County well, to incomplete development of an observation well before sampling. Descriptive statistics for nitrate as N are illustrated graphically by the box plot in figure 29. This indicates a median value of 2.6 mg/L nitrate as N and also indicates that nitrate as N exceeds 4.1 mg/L in only 10 percent of the samples collected in the study area. Contamination of the groundwater of the study area by nitrate as N is not widespread and presently (1979) is not a serious problem.

Irrigation Suitability

Specific-conductance and sodium-adsorption ratio (SAR) ranges for 1977-1979 water samples from the study area are shown on an irrigation-suitability diagram (fig. 30). SAR is an index that relates calcium and magnesium concentrations to the sodium con-

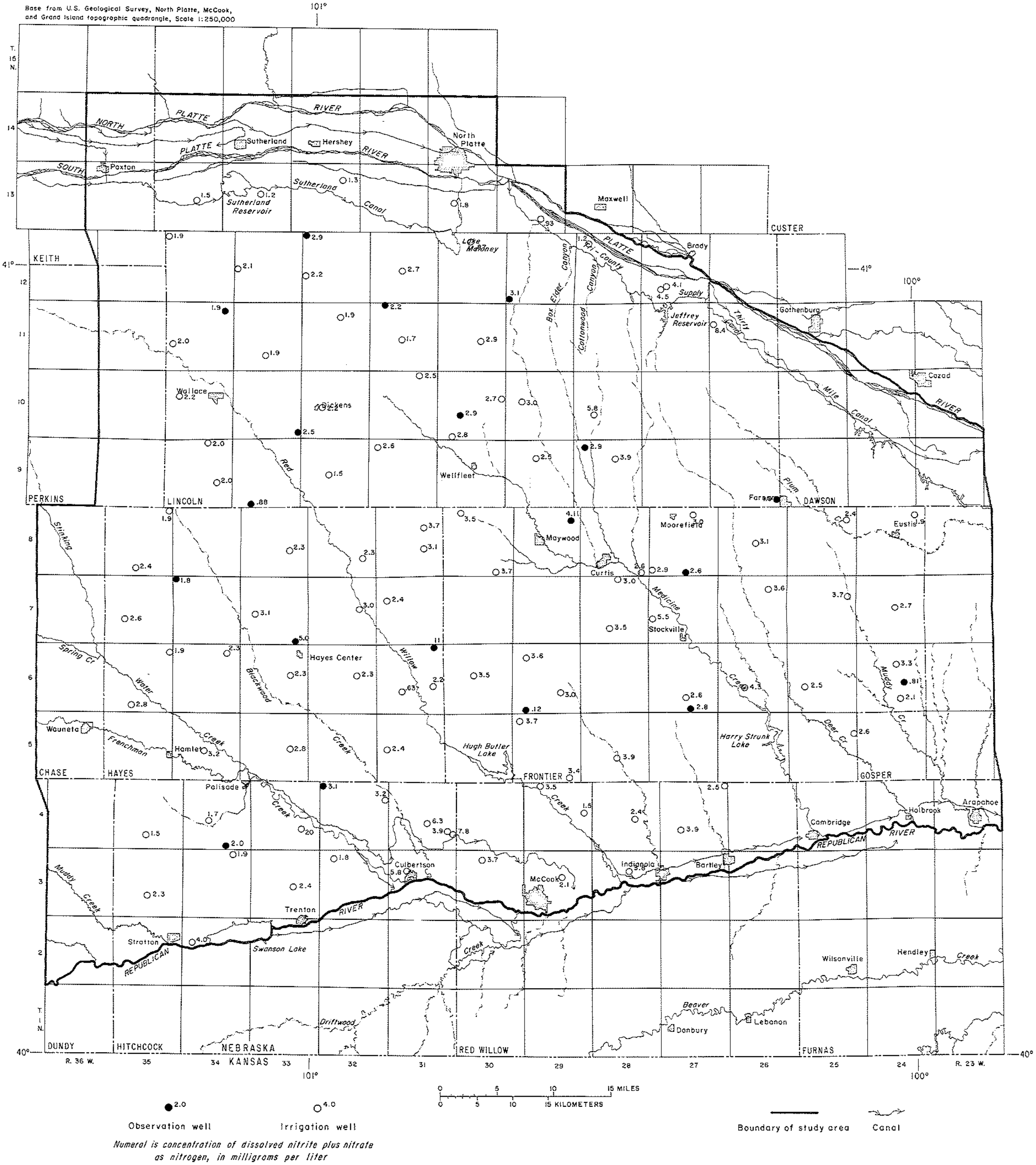


Fig. 28. Concentrations of dissolved nitrite plus nitrate as nitrogen in water from wells sampled from 1977 to 1979.

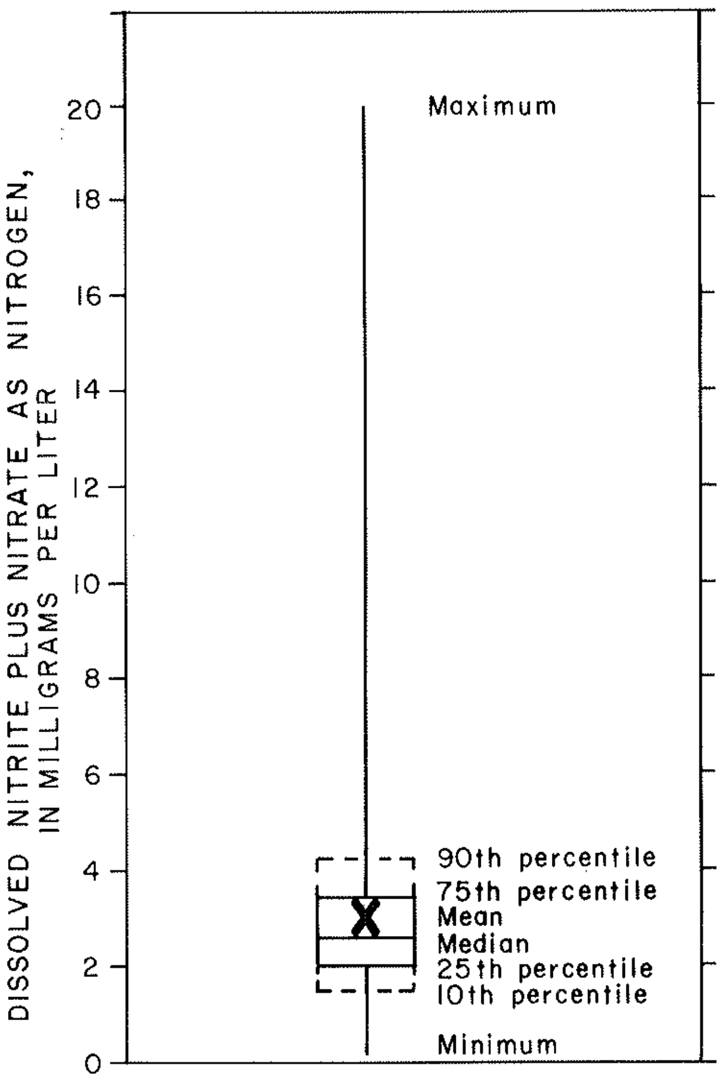


Fig. 29. Descriptive statistics and percentile values for dissolved nitrite plus nitrate as nitrogen in water from 117 wells sampled from 1977 to 1979.

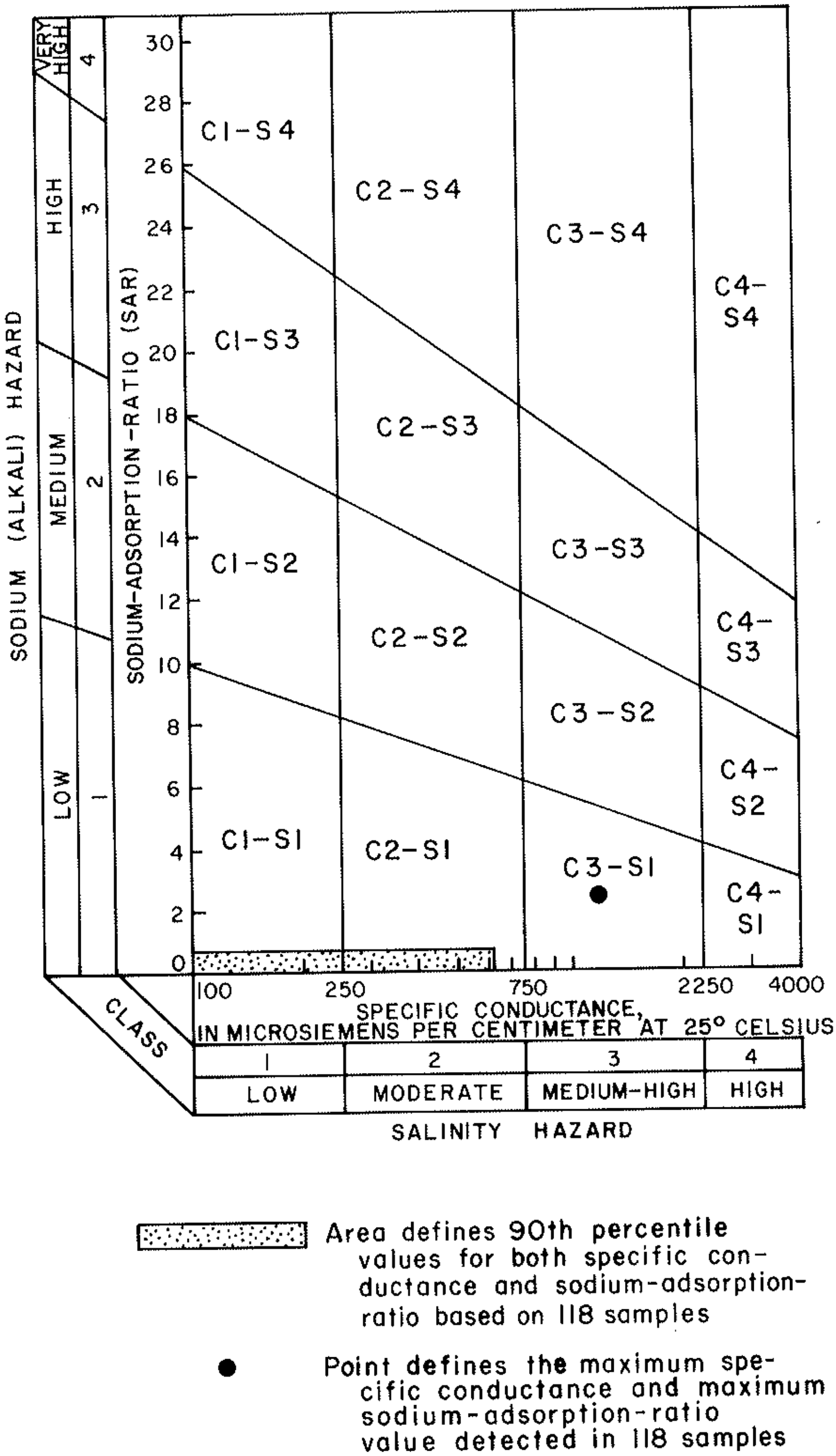


Fig. 30. Suitability of groundwater for irrigation for 1977-1979 water samples (modified from U.S. Department of Agriculture Salinity Laboratory Staff, 1954).

centration in water; generally the greater the sodium concentration, the greater the SAR. On the diagram, water types classified in the lower left area (C1-S1) are most suitable; water types classified in the upper right (C4-S4) are least suitable. Water types classified along the right side of the diagram (C4) have the greatest salinity hazard, and water types classified along the top of the diagram have the greatest sodium hazard. Water classified as C4 generally is unsatisfactory for irrigation because it is too saline for most crops. Water classified as S4 is unsatisfactory for irrigation because large SAR values indicate that sodium may replace adsorbed calcium and magnesium in the soil, causing swelling and damage to its structure. Water classified as C3 can only be used on soils with unrestricted drainage; water classified as S3, if used for irrigation, may require special management of soils.

The 19th percentile value for specific conductance in groundwater in the study area is 616 μS/cm, which means that for more than 90 percent of the samples, the specific conductance does not exceed C2 on the diagram. Likewise, 90th-percentile SAR values are less than one, which is well within S1 on the diagram. C1-S1 and C2-S1 waters are safe for irrigation under most conditions.

The National Academy of Science (1973) recommends that boron concentrations not exceed 750 μg/L. The maximum observed boron concentration in the study area is 350 μg/L, indicating that boron does not constitute a danger to crops grown in the study area.

Simulation of the Hydrogeologic System

The hydrogeologic system was simulated through the use and development of soil-zone and groundwater flow models.

Procedures for Estimating Recharge and Pumpage Data

Recharge and pumpage must be specified to simulate the groundwater system. Measurements of these data are not available for the study area. This section provides information on the procedures used to estimate recharge and pumpage.

Soil-zone Model

Two separate computer programs, the Potential Evapotranspiration (PET) Program and the Soil-Water Program, comprise the soil-zone model. Climate, soil, and crop data are used to estimate consumptive irrigation requirements (CIR) of the crops and to calculate the amount of water that recharges the saturated zone. CIR represents the amount of supplemental water required to maintain the soil root zone at 50 percent of its available water capacity.

The physical basis and operational procedures of the soil-zone model have been discussed by Lappala (1978) and Peckenpaugh and Dugan (1983). Additional information on this model, listings of programs and examples of the input data and the output are included in Cady and Peckenpaugh (1985).

The PET Program computes potential ET using the Jensen-Haise method (Jensen and others, 1969) for 18 weather stations in or near the study area. First, it computes total solar radiation for each year and month by a regression equation using percentage of possible sunshine and mean daily solar radiation for each month. Next, it calculates monthly potential ET using mean monthly air temperature, the mean minimum and maximum air temperatures for the warmest month of the year, and monthly total solar radiation. The locations of the weather stations are shown on figure 11. Thiessen polygons are also shown on this figure so that each element could be assigned to a weather station. The weather stations and soil groups are placed on the same figure because these parameters are closely related in the modeling process.

For the PET Program, precipitation values are available for each weather station, but air-temperature data are not. The mean monthly air temperatures for weather stations at Culbertson, Hayes Center, and North Platte were assigned to the other weather stations according to their location. If air-temperature or precipitation data were missing, they were estimated by linear regression with data from adjacent stations. The data on percentage of possible sunshine and mean daily solar radiation on cloudless days were available only for the National Weather Service station at North Platte and were used throughout the study area.

The PET Program creates a file with monthly precipitation, mean monthly air temperature, and monthly potential ET. However, as mentioned previously, the only new parameter computed is monthly potential ET. This file becomes input data for the Soil-Water Program.

The second computer program in the soil-zone model is the Soil-Water Program, which simulates the infiltration, storage, and removal of water from the soil on a monthly basis. The Soil-Water Program uses the following data: monthly precipitation; monthly potential ET; monthly precipitation-infiltration curve coefficients; curve numbers that are dependent on the soil, land use, and topography; water-holding capacity of the soil; and monthly crop coefficients. Four nested loops—weather station, land use, soil, and monthly time increments—are used to compute monthly values of infiltration, surface runoff, deep percolation, soil moisture, consumptive irrigation requirements, and water shortage for irrigated and non-irrigated conditions for each land use, soil, and weather station. Options are available to compute and print seasonal (irrigation and non-irrigation periods), annual, and total simulation-period summaries of the monthly parameters previously mentioned. However, the primary purpose of this program is to compute recharge to the saturated zone and consumptive irrigation requirements, which are needed in simulating the hydrogeologic system. If additional information is needed on this program, consult Cady and Peckenpaugh (1985).

The amount of monthly infiltration through the soil surface is dependent upon the amount and intensity of precipitation, topography of the land surface, soil lithology, vegetative cover, and previous soil moisture. Four monthly precipitation-infiltration curves developed from empirical data (precipitation and surface-runoff) for sites near Rosemont, Nebraska, are shown on figure 31 (Fred Otradovosky, oral communication). Each curve is dependent upon soil lithology, topography, and land use. The chart illustrates the possible combinations of soil lithologies, topographies, and land uses used to generate each curve. The shapes of these curves could be adjusted, but only after evaluating the original data. This evaluation was beyond the scope of the current study.

The appropriate curve in figure 31 is selected based on soil group, topography, and vegetation. The water-holding capacity and curve values used for the seven soil groups in the study area are listed in table 11.

Crop coefficients for different times of the year are shown in figure 32. These coefficients were modified from Lappala (1978) by using a coefficient of 1 for row crops during July and by lowering the coefficient for pasture and range from July through October. Crop coefficients are the ratio of consumptive water requirement (CWR) to potential ET. CWR is the seasonal or monthly water demands of a crop in relation to potential ET. The consumptive water requirement is the amount of water required by vegetation types based upon their growth or physiological characteristics.

Differences in the CWR/potential-ET ratio for the five land uses and for the seasonal changes within each land use are shown in figure 30. Most crops have low CWR/potential-ET ratios during the nongrowing season when they are dormant, and they have larger and usually more variable ratios or crop coefficients during the growing season.

Results from the Soil-Water Program include the annual estimates of the following items for each soil group, land use, and weather station for 1935 to 1978: 1) infiltration; 2) ET; 3) surface runoff; 4) irrigated land recharge; 5) CIR; 6) dryland recharge; and 7) dryland water shortage. Results from the Soil-Water Program for the soil groups that occur in the area enclosed by the Thiessen polygons identified with the Curtis, McCook, North Platte, and Wallace weather stations are given in appendix B. These weather stations were selected for this table because they generally represent the range of land use, soils, and climate in the study area.

The results from the Soil-Water Program can be reviewed through the use of the following three equations:

1) P = I + RO;
2) ET = I - DPI + CIR + SMI; and
3) ET = I - DPD + STD + SMD

where:

P = precipitation;
I = infiltration;
RO = surface runoff;
ET = evapotranspiration;
DPI = deep percolation (recharge) from irrigated lands;
CIR = consumptive irrigation requirement;
SMI = soil moisture on irrigated lands;
DPD = deep percolation (recharge) from drylands;
STD = water shortage of drylands; and
SMD = soil moisture on drylands.

Using the equations above with the first soil group in appendix B will enable the user to determine the following items: 1) the average precipitation at Curtis (20.1 in.) equals the summation of infiltration and surface runoff (equation 1); and 2) The SMI and SMD parameters were not listed in appendix B; they represent the amount of soil moisture necessary to balance the right and left sides of equations 2 and 3.

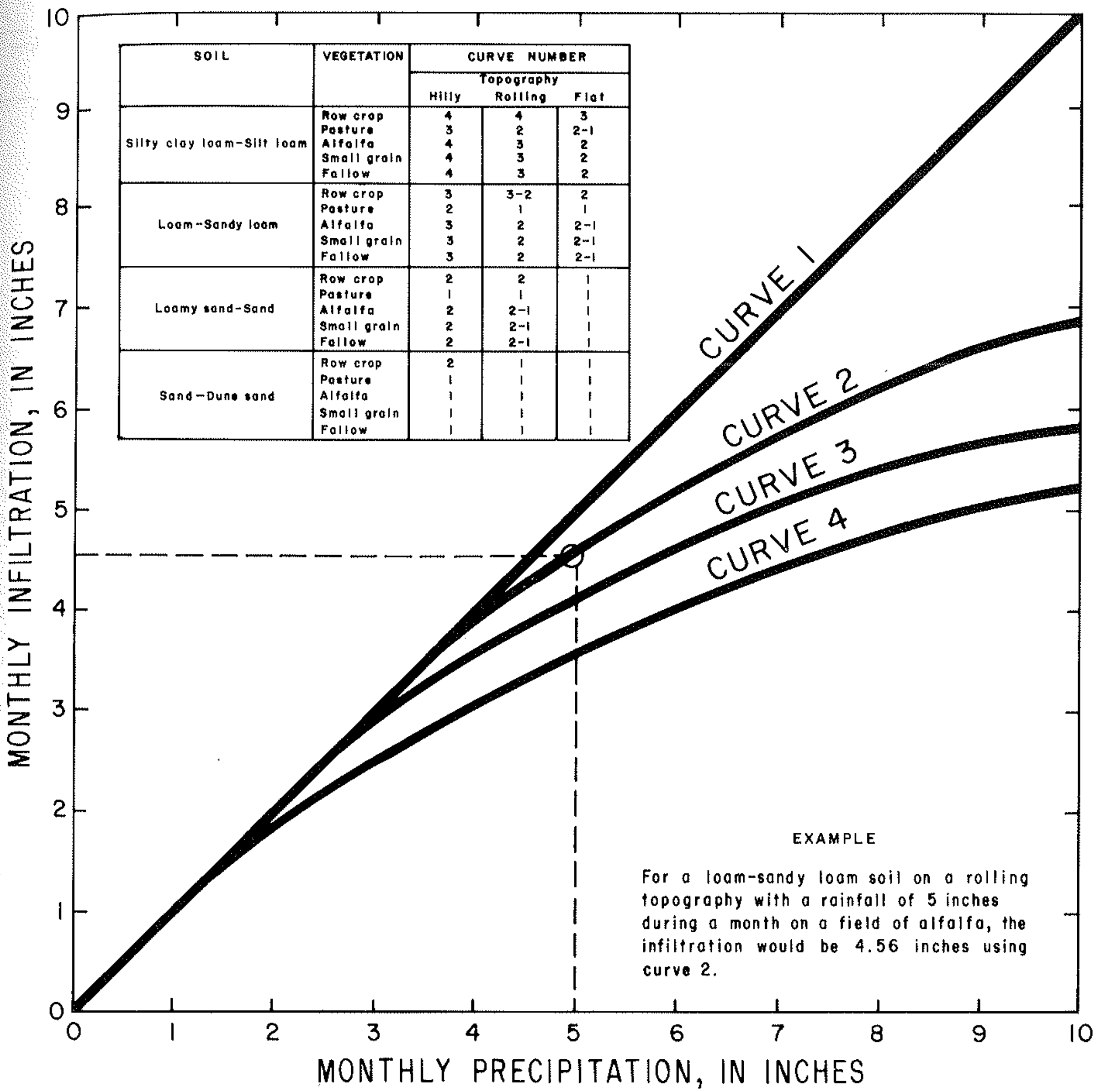
An examination of appendix B and table 11 illustrates the significance of available water-holding capacities and precipitation-infiltration curve numbers of the different soil groups. For example, using the Curtis weather station, the Colby-Ulysses and Coly-Uly associations and Bankard-Las-Glenberg and McCook-Munjor-Inavale associations have available water-holding capacities of 0.16. Their curve numbers are 3 and 2, respectively, for row crops. The Colby-Ulysses and Coly-Uly associations have lower infiltration (18.3 in.) and recharge values (1.3 in. for DPI and 0.95 in. for DPD) than do the Bankard-Las-Glenberg and McCook-Munjor-Inavale associations, which have infiltration and recharge values of 19.2 in. for I, 1.8 in. for DPI, and 1.4 in. for DPD. These results are caused by the larger curve number for the Colby-Ulysses and Coly-Uly associations, which causes a lower infiltration value. Also, soil groups and land uses with similar curve numbers but different available water-holding capacities will have different recharge values. Recharge values increase as the water-holding capacities decrease.

Appendix B also illustrates how the different soil-moisture parameters like ET and recharge vary as the land uses change. Generally, ET increases and recharge decreases within the land uses as follows: small grain, fallow, row crop, pasture, and alfalfa.

The Soil-Water Program was adjusted by comparing its results with either measured or estimated values of surface runoff, recharge, and consumptive irrigation requirements. When adjustments were necessary, they usually were made by changing the available water-holding capacities or the curve numbers.

Recharge-discharge Model

The computation of recharge and discharge from the groundwater system requires data from a variety of sources. Much of these data are not measurable directly; therefore, procedures were developed to es-



SOIL	VEGETATION	CURVE NUMBER Topography Hilly	Rolling	Flat
Silty clay loam–Silt loam	Row crop	4	4	3
	Pasture	3	2	2-1
	Alfalfa	4	3	2
	Small grain	4	3	2
	Fallow	4	3	2
Loam–Sandy loam	Row crop	3	3-2	2
	Pasture	2	1	1
	Alfalfa	3	2	2-1
	Small grain	3	2	2-1
	Fallow	3	2	2-1
Loamy sand–Sand	Row crop	2	2	1
	Pasture	1	1	1
	Alfalfa	2	2-1	1
	Small grain	2	2-1	1
	Fallow	2	2-1	1
Sand–Dune sand	Row crop	2	1	1
	Pasture	1	1	1
	Alfalfa	1	1	1
	Small grain	1	1	1
	Fallow	1	1	1

Fig. 31. Relation of monthly infiltration to monthly precipitation.

Table 11. Water-holding capacity and infiltration-precipitation curve numbers for soil groups

[Curves are given in figure 31]

Soil group	Available water holding capacity[a] (inch/inch)	Precipitation-infiltration curve numbers				
		Row crop	Alfalfa	Small grain	Pasture	Fallow
Holdrege-Hall, Keith-Goshen, and Rosebud-Alliance-Kuma Associations	0.21	2	2	2	1	2
Colby-Ulysses and Coly-Uly Associations	0.16	3	3	3	2	3
Hobbs-Hord-Cozad Association	0.17	2	2	2	1	2
Jayem-Sarben and Vetal-Hersh Associations	0.13	2	1	1	1	2
Valentine and Valent-Tassel Associations	0.07	2	1	1	1	2
Bankard-Las-Glenberg and McCook-Munjor-Inavale Associations	0.16	2	2	2	1	2
Lawet-Wann-Lex Association	0.13	1	1	1	1	1

[a]Source: U.S. Soil Conservation Service (1978)

timate them. These procedures comprise the recharge-discharge model.

This model consists of two computer programs; the Twin Platte-Middle Republican Pumping Program (TPMRPUMP) estimates the recharge and discharge values for the calibration period and the Twin Platte-Middle Republican Prediction Program (TPMRPRED) estimates recharge and discharge values for the predictive scenarios. The output from these two programs is used as input to the groundwater flow model. TPMRPUMP and TPMRPRED programs are documented by Cady and Peckenpaugh (1985).

The TPMRPUMP Program calculates the net recharge or discharge by pumping periods, a 3-month irrigation period from June through August and a 9-month non-irrigation period for the remainder of the year for each element in the modeled area during the calibration period. The following items are data for this program: annual canal diversions and returns; annual seepage rates from canals and lakes; surface water applied per acre; area of each element; land use by county and year; and deep percolation and CIR estimates by land use, soil, and weather station. The TPMRPUMP Program uses an outer time loop and inner-element (triangular or quadrilateral area) loop to compute the net recharge or discharge as mentioned above based on a water-use system which may include surface-water, groundwater, and groundwater-supplemented, surface-water irrigated lands.

The TPMRPRED Program is a modification of the TPMRPUMP Program. It calculates the net recharge or discharge for different groundwater-irrigation development rates and for future irrigation application rates.

Assumptions in the Procedures

Several assumptions were required to apply the recharge-discharge model. The most significant assumptions are as follows.

Measurements of seepage losses are not available for any of the surface-water irrigation canals between the North Platte and South Platte rivers or for the Thirtymile, Sixmile, and Orchard and Alfalfa canals. For these canals, it was assumed that 50 percent of the surface water diverted was applied as irrigation water and that the other 50 percent became seepage losses that recharged the aquifer at the irrigation site. Also, it was assumed that 70 percent of the annual diversion was during the irrigation pumping season (June through August) and that the remainder of the diversion was during April and May of the non-irrigation pumping season (Jess, Nebraska Department of Water Resources, oral communication).

The seepage losses for the other canals in the study area—the Sutherland and Tri-County Supply canals and the U.S. Bureau of Reclamation canals along the Republican River—are assumed to occur along the main canals. These seepage losses were discussed in a previous section of this report.

If the amount of surface water applied is more than the consumptive irrigation requirement (CIR) for a given element, the surplus surface water is assumed to recharge the aquifer. If the applied water is less than the CIR for a given element, the deficit is assumed to be made up by pumping groundwater if an irrigation well exists in the element.

Acreages irrigated with groundwater are computed by multiplying the number of irrigation wells per element by the acres irrigated per well. Information on the number of registered irrigation wells and acres irrigated per well for 5-yr intervals by county is listed in table 12. Data on irrigated acres were obtained from the annual reports, "Nebraska Agricultural Statistics" (Nebraska Department of Agriculture, 1935-1978), and

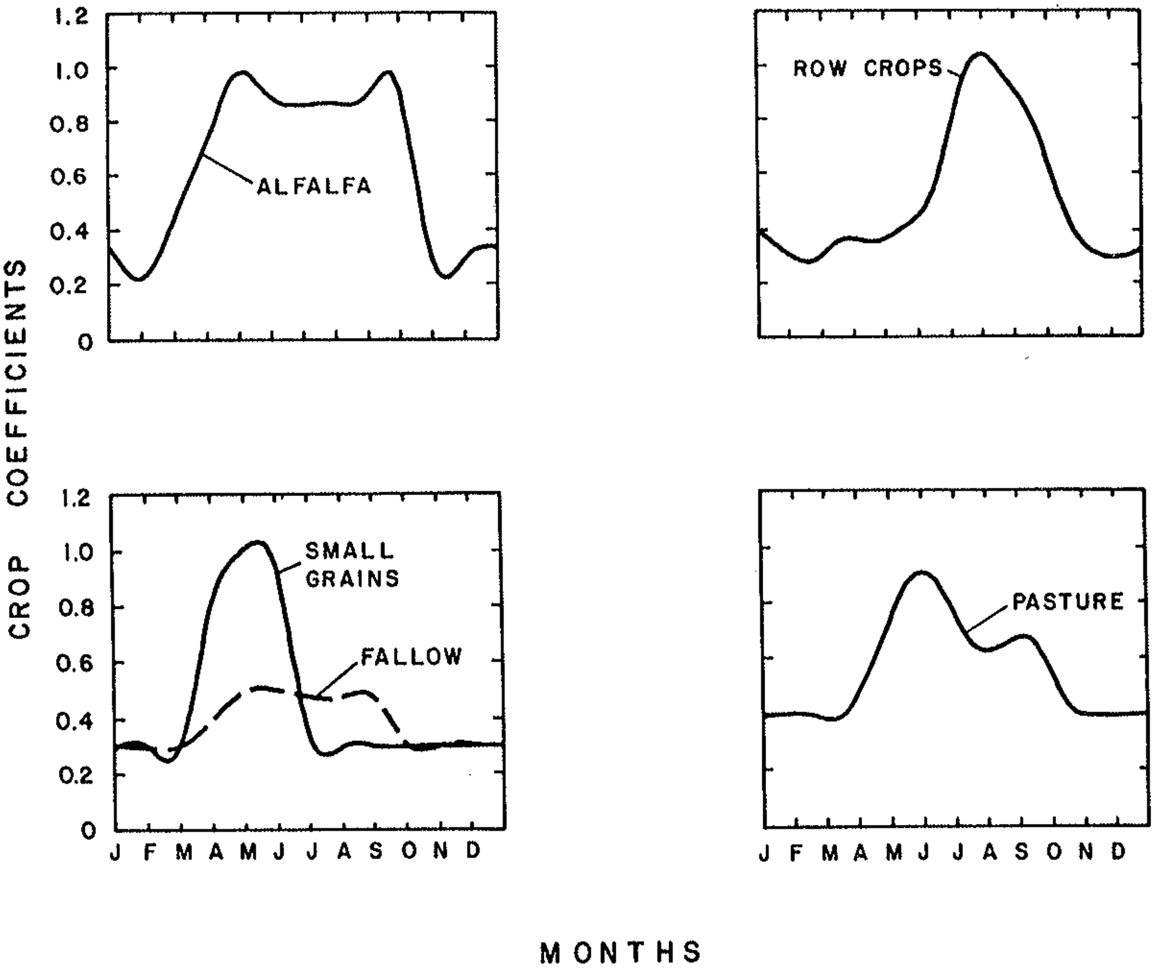


Fig. 32. Monthly crop coefficients for alfalfa, row crops, small grains, fallow, and pasture.

data on registered irrigation wells were obtained from the Nebraska Department of Water Resources. This procedure was verified for central Nebraska by Peckenpaugh and Dugan (1983), and it is assumed to be valid for this study area.

Water-level declines caused by groundwater withdrawals for domestic, stock, industrial, and most municipal purposes are assumed to be insignificant regionally. Therefore, groundwater usage for these purposes, except for the city of North Platte (table 13) was not included in the recharge-discharge model.

The volume of groundwater pumped is obtained by multiplying the computed irrigated acres by the CIR for the land use(s) that occur in the element. An assumption is made that sufficient water will be applied by irrigation to satisfy the CIR for that particular use.

Information for each land-use category is available on a county basis for each year; however, comparable information on a farm-by-farm basis is not available. Thus, the assignment of acreages to different land-use categories for individual elements for different time periods is not practical. The U.S. Soil Conservation Service developed a land-use map that covers the entire study area (SCS, 1977, written communication). Using this information, acreages were assigned to each of the five possible land-use categories for each element. The acreages so assigned were assumed not to vary except for additional groundwater irrigation acres. Based upon irrigation practices in the study area, new irrigated lands were row crops, which initially replaced dryland row crops. Eventually, as more land was irrigated, dryland pasture and range and dryland small grains were converted to irrigated row crops.

The assumption also was made that ET from shallow groundwater areas was insignificant except for valleys of the Platte and Republican rivers. Even in these areas, ET from the groundwater was not considered in the groundwater flow model.

Input and Output for Recharge-discharge Model

The input data and output for the recharge-discharge model are very similar for the TPMRPUMP and TPMRPRED programs. The input data for these programs are as follows: canal diversions and returns (table 2); municipal groundwater pumpage for North Platte (table 13); number of wells per element; results from the Soil-Water Program (appendix B); land-use data; and acres irrigated per well (table 12).

The output from the TPMRPUMP and TPMRPRED programs are the net recharge or discharge for each element for each pumping period. These results are used in the groundwater model as previously mentioned. However, the total net recharge or discharge was calculated for the study area for each pumping period.

Appendix B contains information on pumpage estimates (CIR) and recharge (DPI and DPD) by weather station, soil group, and land use. For example, at the Curtis weather station using the first soil group and row crop, the CIR or required pumpage for maximum yield was 12.7 in.; the recharge on irrigated lands was 1.1 in.; and recharge on drylands was 0.61 in. Similar pumpage and recharge values can be obtained for the other land uses and soils. Annual recharge for the study area during 1978 was estimated at 222,300 acre-ft, while pumpage of groundwater was estimated at 240,000 acre-ft.

Procedures for Developing the Groundwater-flow Model

The model used to simulate the groundwater system was developed during this project and is described by Cady and Peckenpaugh (1985). Throughout this report, the model will be referred to as "RAQSIM," an acronym that stands for regional aquifer simulation. RAQSIM is a two-dimensional, finite-element program developed to solve regional groundwater flow problems. Two-dimensional groundwater flow often is represented mathematically by an equation generally referred to as a two-dimensional diffusion equation. RAQSIM is used to approximate the solution to this equation applied over the modeled area.

Assumptions Inherent in the Two-dimensional Diffusion Equation

The processes governing the flow of groundwater may be described mathematically by approximating equations. While these equations are almost universally accepted, it should be noted that they only approximate the physical system. For example, while groundwater flows between individual particles of aquifer material, generally it is described mathematically over a much larger scale without reference to particles and detailed flow paths.

The particular model for this project incorporates additional major assumptions. They are:

1) No vertical flow within the aquifer;
2) The validity of Darcy's law over the full range of conditions simulated;
3) Water instantaneously released from storage within the aquifer.

While these assumptions often are reasonable, some may lead to problems trying to relate the response of the model to the response of the physical system. Some of these problems will be discussed later in this report.

Assumptions in Modeling

Numerical simulation techniques to simulate groundwater flow generally require that the modeled area and the time period be made into discrete units. Finite-element techniques generally separate the aquifer into a limited number of triangular or quadrilateral areas called elements. Nodal points or nodes are located at the vertices of the triangles and quadrilaterals. The equations are solved in an average sense over

Table 12. Registered irrigation wells and acres irrigated per well by county

[Generated from data of the Nebraska Department of Water Resources.]

County	1935-39		1940-44		1945-49		1950-54		1955-59		1960-64		1965-69		1970-74		1975-78	
	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well
Chase	8	40	14	62	22	31	47	47	113	72	149	70	331	92	695	101	1094	100
Dawson	243	76	473	83	708	37	988	45	1830	52	2048	41	2188	32	2413	40	2799	48
Dundy	4	40	7	34	13	35	33	33	89	72	111	68	175	93	33	103	667	88
Frontier	1	40	2	40	4	37	12	53	75	81	104	93	168	86	338	103	559	98
Furnas	12	30	22	69	31	44	52	49	156	44	201	43	249	42	347	55	496	60
Gosper	7	58	19	50	25	45	36	59	107	62	137	60	198	58	331	76	500	80
Hayes	8	41	11	66	12	25	18	61	42	55	61	33	90	45	164	61	262	67
Hitchcock	17	35	28	48	37	21	63	20	138	35	164	59	186	38	249	50	336	56
Keith	40	48	74	42	110	15	159	15	253	46	324	37	411	36	548	48	716	57
Lincoln	72	40	124	37	170	30	253	20	431	29	542	21	644	22	824	41	1218	52.0
Perkins	1	40	3	33	4	39	15	21	39	84	51	87	99	93	253	124	580	129.0
Red Willow	14	40	34	55	59	27	80	23	169	36	202	61	242	87	381	88	588	76

Table 13. Municipal pumpage of North Platte[a]

Interval (years)	Non-irrigation[b] period (acre-feet)	Irrigation[b] period (acre-feet)
1935-50[c]	1,560	894
1951-55	2,043	1,337
1956-60	1,930	1,315
1961-65	2,284	1,613
1966-70	2,491	1,977
1971-75	3,126	2,633
1976-78	3,356	2,636

[a] Data obtained for the period 1949-1978 from the city of North Platte.
[b] Non-irrigation period is from September through May, and irrigation period is from June through August.
[c] No data available before 1949. The 1949 and 1950 pumpages were assumed to adequately represent the 1935-1950 pumpage.

areas associated with each node; they are not solved exactly at every point in the aquifer. Because time also is divided into discrete units, water levels are estimated at specific moments rather than continuously.

While hydraulic properties such as transmissivity, specific yield, and sources of water to or from the aquifer vary continually over the modeled area, the actual input to the model must be in the form of discrete values at a finite number of locations within the modeled area. In RAQSIM, transmissivity and specific yield are represented by block estimates constant over elements or larger areas. The water level and the base of the aquifer are represented by point values at nodal points with linear variation across an element.

Representing the Hydrogeologic System in the Groundwater Model

The finite-element grid (fig. 33) consists of 1,182 triangular and quadrilateral elements. Generally, townships were divided into at least four elements with additional elements added to adequately portray surface-water bodies, stream reaches, and township adjustments. Transmissivity and specific yield were approximated from existing point-value estimates that were used in developing the transmissivity and specific-yield maps (figs. 23 and 24). The modeled variation in transmissivity was qualitatively examined during the calibration phase and is discussed further in that section.

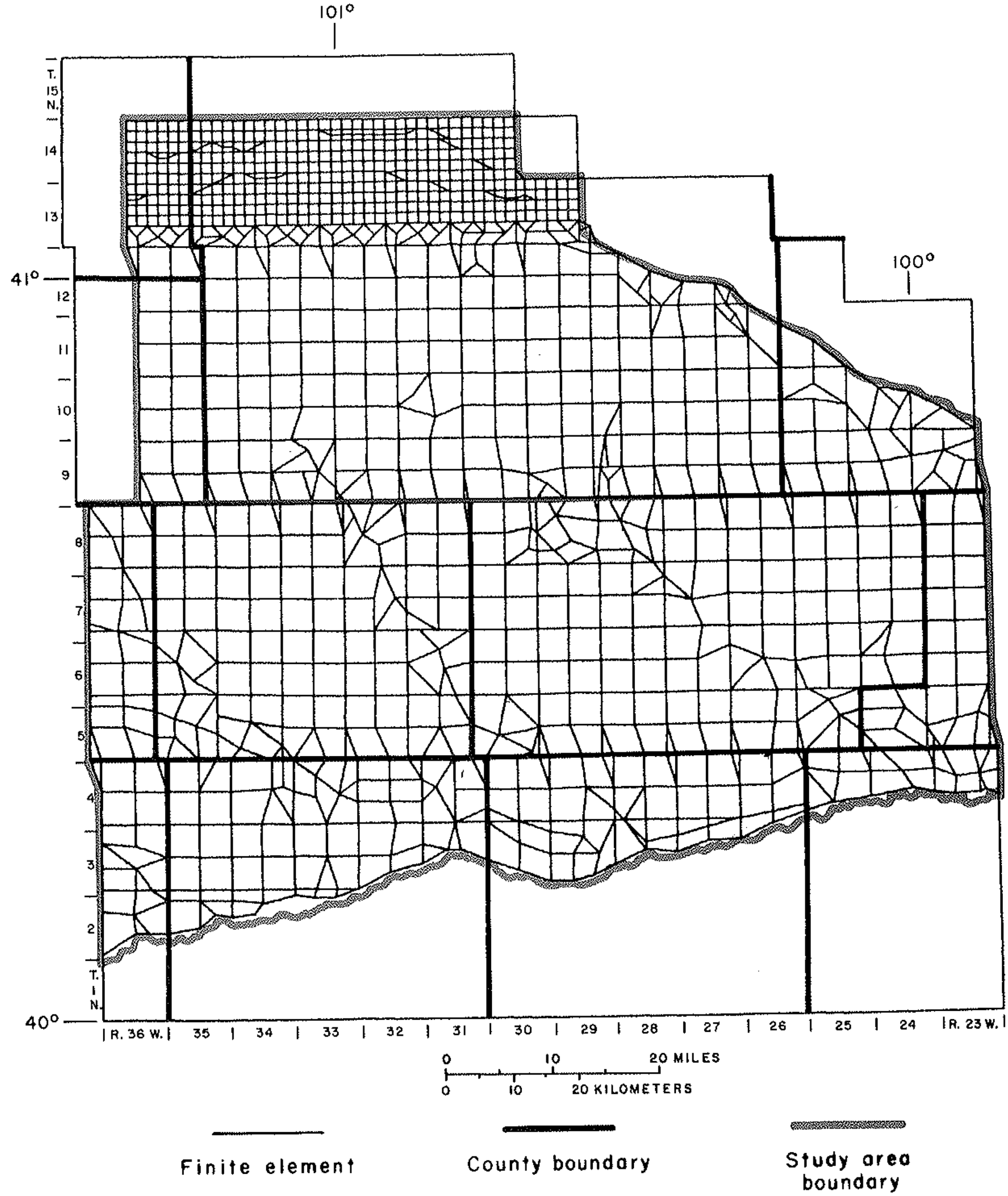


Fig. 33. Finite-element grid for groundwater model.

The elevation of the base of the aquifer at each node was determined by interpolating from the contoured base of the aquifer map (fig. 22).

Two sets of water levels at each node were determined by interpolating from contoured maps of predevelopment and 1977-1978 water levels (figs. 18 and 19). Some water levels were adjusted because of the following conditions: 1) near some canals and surface-water impoundments, the occurrence of significant vertical seepage required some adjustments in the interpretation of average water levels; 2) the elevation of the water table adjacent to a canal or surface-water impoundment had been assumed to be equal to the elevation of the water surface within the surface-water body, but these elevations had to be adjusted because the average water level throughout the saturated thickness adjacent to the surface-water body was somewhat less than the elevation of the water table.

At stream nodes, the seepage between a stream and the underlying aquifer was simulated by approximating the flux as proportional to the difference in the water level between the aquifer and the stream. Stream baseflow was approximated by summing the stream-aquifer flux along the stream course. Seepage from lakes and canals was approximated from the historical data and represented in the model as a known-flux quantity.

Evaporation or transpiration from groundwater was not simulated as a part of this project. Because of the limited areal extent of shallow groundwater (water levels within 5 or possibly 10 ft of land surface) and the presence of streams or drains located near where shallow groundwater might exist, omission of this mechanism would be of little significance relative to the overall usefulness of the model. The largest area of shallow groundwater exists between the North Platte and South Platte rivers. Both of these rivers were modeled as known-head nodes, which forced the nodes between the two rivers to maintain a fairly constant head regardless of the fluxes that may occur. Thus, evaporation or transpiration from the groundwater would not be significant from these areas. Also, a somewhat similar situation exists with nodes along the Platte and Republican rivers, where these streams also were simulated as known-head nodes.

Recharge and discharge estimated from either TRMRPUMP or TPMRPRED were separated into two periods of constant recharge or discharge. Since individual wells were not simulated, there were no obvious means available to accurately represent the decrease of well yield as saturated thickness decreases. Therefore, discharges were not decreased as saturated thicknesses of the aquifer decreased; however, discharge was set to zero at nodes where the simulated water level fell below the base of the aquifer.

The southern boundary of the modeled area is the south side of the Republican River. Because of the limited aquifer south of the river, this boundary was approximated as a no-flow boundary. Since the river is included in the stream network, flow from the aquifer or to the aquifer along this boundary is simulated by flow to or from the river. Throughout the simulation, the northern boundary at the North Platte and Platte rivers was considered a known-head boundary with the water level fixed at the approximate elevation of the water surface in the river.

The lower boundary of the system is approximated by the base of the aquifer and is simulated as a no-flow boundary. The upper boundary of the system is the water table. This boundary is simulated as a known-flux boundary in the general case of prescribed recharge or discharge to the aquifer.

Treatment of the east and west boundaries during simulations of the future differed from the treatment within the simulation of the historical period. Discussion of these boundary conditions is included in the sections describing the respective simulations.

Simulation of Historical Period

The predevelopment water level (fig. 18) was assumed to represent the initial condition for simulations over the historical period, 1935-1978. The east and west boundaries of the model were considered known water-level boundaries with the water level varying linearly over time from the water level estimated for 1935 to the water level estimated for 1977-1978.

Sensitivity

Throughout the discussion of the sensitivity analysis and calibration process, references will be made to weighted residuals. In the context of this report, a weighted residual is the difference between the estimated water level and the simulated water level weighted by the area associated with the node. Therefore, widely spaced nodes will contribute more to the average than will closely spaced nodes. This will give a better representation than just the average of the nodal values alone. Weights at known-head nodes are set to zero to eliminate their influence. The average weighted residual is calculated by summing the products of the nodal residual and the nodal weights and dividing the resultant sum by the sum of nodal weights. The root-mean square weighted residual is calculated by summing the product of the squared nodal residuals and the nodal weights, dividing the resultant sum by the sum of nodal weights and finally taking the square root.

Overall sensitivity of the model to transmissivity, specific yield, recharge and discharge was evaluated by multiple simulations of the historical period, where only one parameter was varied per simulation. Generally, the simulated water table is most sensitive to recharge or discharge and more sensitive to specific yield than to transmissivity. However, the baseflow of the streams, which represents groundwater's contribution to streamflow, is least sensitive to specific yield and almost equally sensitive to transmissivity and recharge or discharge.

Calibration

The process of calibration generally is an iterative process whereby the simulated results of a hydrogeologic system are compared with the observed behavior of the system over the same historical period. Hydrogeologic parameters may be modified within realistic bounds to improve the ability to simulate the observed behavior and better understand the system.

Optimized Transmissivity Estimation

A procedure detailed by Neuman and Yakowitz (1979), Neuman and others (1980), and Neuman (1980) was used to calibrate the model to steady-state conditions by adjusting transmissivity estimates. This procedure employs steady-state water levels and flux estimates, and initial estimates of transmissivity to refine transmissivity estimates. Transmissivity is zoned and therefore may be represented within the range of one value for the entire area to one value per element.

Steady-state simulations were used to evaluate the sensitivity of the model to zoning transmissivity by township versus zoning transmissivity by element. Initial township-zoned estimates for transmissivity (fig. 34) were derived by determining the average (mean) of point estimates for transmissivity within each township. If there were no point estimates within a township, the nearest point estimate served as the township estimate. Zoning the transmissivity by township was acceptable relative to the response of the hydrogeologic system with element transmissivity determined by point estimates of transmissivity values within each element. Simulated 1970s water-level configuration maps prepared using element transmissivity values and initial estimated transmissivity values by township (fig. 35) compared favorably, with a maximum water-level difference of approximately 20 ft. The measured 1977-1978 water levels (fig. 19) and the simulated 1970s water levels developed from initial estimated transmissivity values by township also were compared. Differences between these water levels were within about 25 ft except in the southeastern corner of the study area, where the simulated water levels were unable to match water levels in the stream valleys (fig. 36).

From the standpoint of the transmissivity adjustment procedure, it is preferable to have the fewest number of transmissivity zones that adequately represent the variability of transmissivity. Also, the simulated 1970s water levels were reasonably similar for element transmissivity values and initial estimated transmissivity values by township. Therefore, zoning transmissivity by township was used in the groundwater model.

Predevelopment Conditions

Assuming that the predevelopment water-level configuration represents essentially an equilibrium condition resulting from average recharge and discharge before substantial water-resources development, model calibration depends upon reliable values of the water level and flux estimates. The steady-state flux distribution before substantial water-resources development was estimated by combining the average recharge and discharge for 1935-1944 with the stream-aquifer seepage estimates from the seepage runs of the late 1970s. The computed steady-state water levels were an average of 130 ft higher (root-mean-square residual of 157 ft) than the estimated predevelopment water-level configuration. Such a poor initial fit suggests that there may be problems in the data beyond the acknowledged uncertainty in the transmissivity estimates. Representing streamflow during the 1930s and 1940s by streamflow observed during the late 1970s may contribute somewhat to the poor fit, as well as the estimates made for the equilibrium recharge and discharge for the predevelopment period. Because of these problems, transmissivity adjustments were not based upon predevelopment steady-state conditions.

1970s Conditions

It is assumed that near-equilibrium conditions existed throughout the modeled area during the 1970s. Therefore, the procedures to optimize transmissivity values previously mentioned can be used on the 1970s conditions because near-equilibrium water levels existed and flux values are available for this time period.

Individual flux values were averaged for 1969 through 1978, and the steady-state water-level estimate was approximated by the 1977-1978 water-level configuration. Flux to streams was assumed to equal the amount estimated by seepage measurements recorded during the fall of 1978. Water levels on the eastern and western boundaries were assumed to be constant, as were water levels along the boundaries defined by the Platte River, North and South Platte rivers, and the Republican River.

The adjusted estimates for transmissivity for each township based on this simulation are given in figure 36. With the initial estimated transmissivity values by township, computed steady-state water levels for the 1970s (fig. 37) averaged 25 ft above the observed 1977-1978 water levels (root-mean-square residuals of 44 ft). Comparing figure 35 and figure 38 (the simulated 1970s steady-state water levels using adjusted estimated transmissivity values by township and the observed 1977-1978 water levels), it is apparent that the adjusted transmissivity (fig. 38) allows a closer steady-state approximation to the observed water levels in 1977-1978. The computed steady-state water levels after the transmissivity estimates had been adjusted during the simulation were on the average 5 ft above

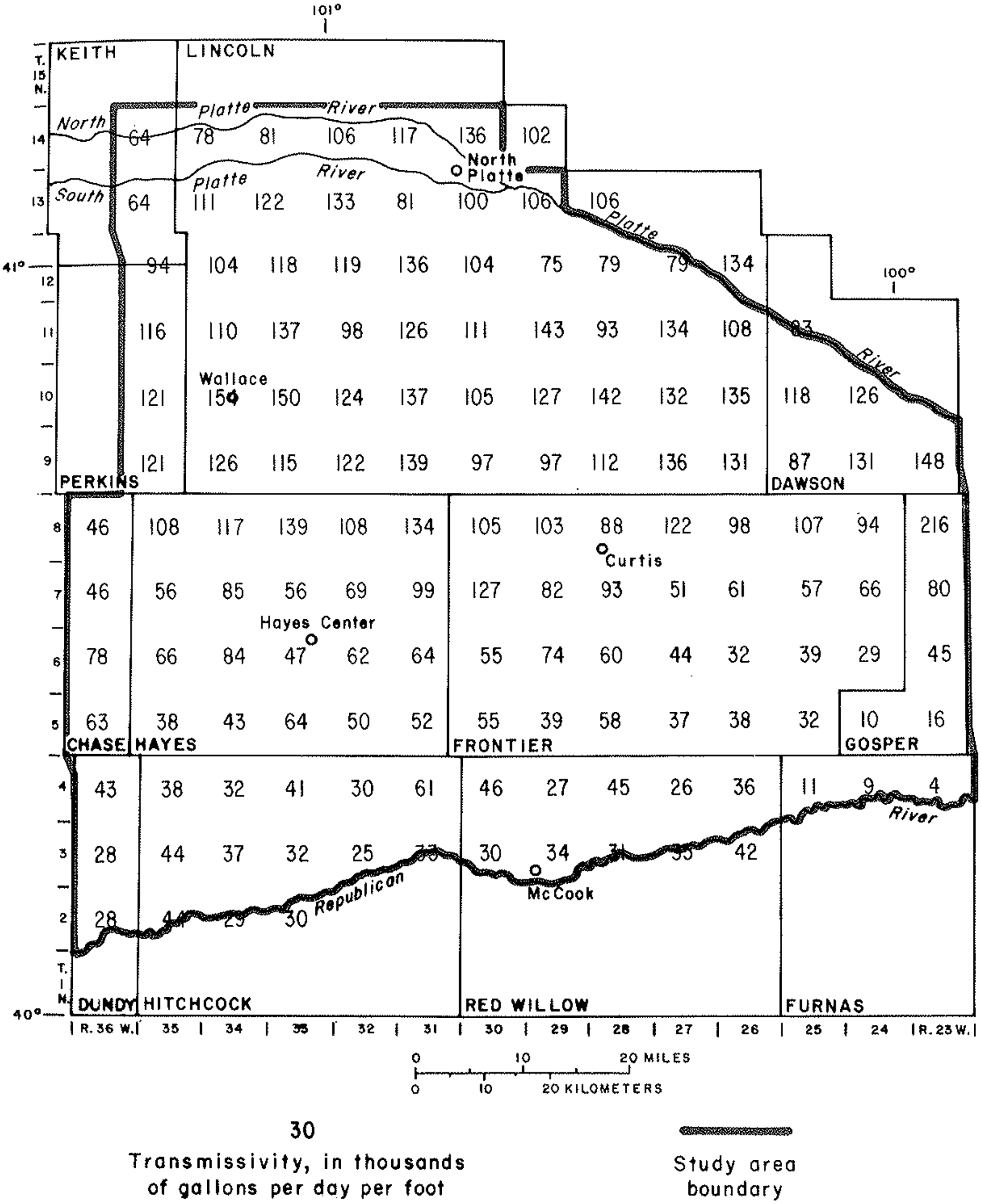
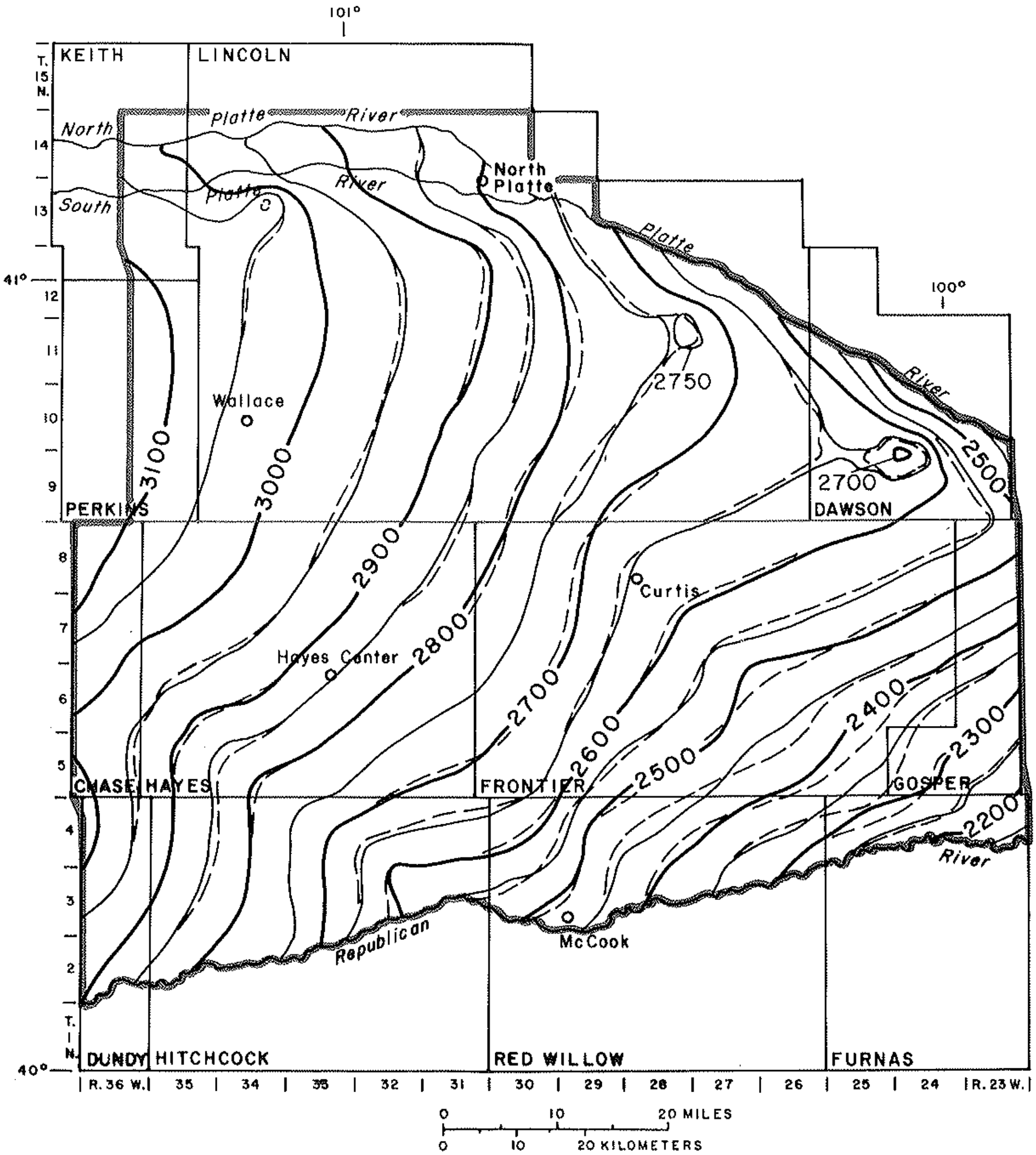


Fig. 34. Initial estimated transmissivity values.



—3100—

Line of equal water level

Simulated altitude using element transmissivity values Interval is 50 feet.

---3100---

Line of equal water level

Simulated altitude using initial estimated transmissivity values by township Interval is 50 feet.

Study area boundary

Fig. 35. Simulated 1970s steady-state water levels using initial estimated transmissivity values by township and element transmissivity values.

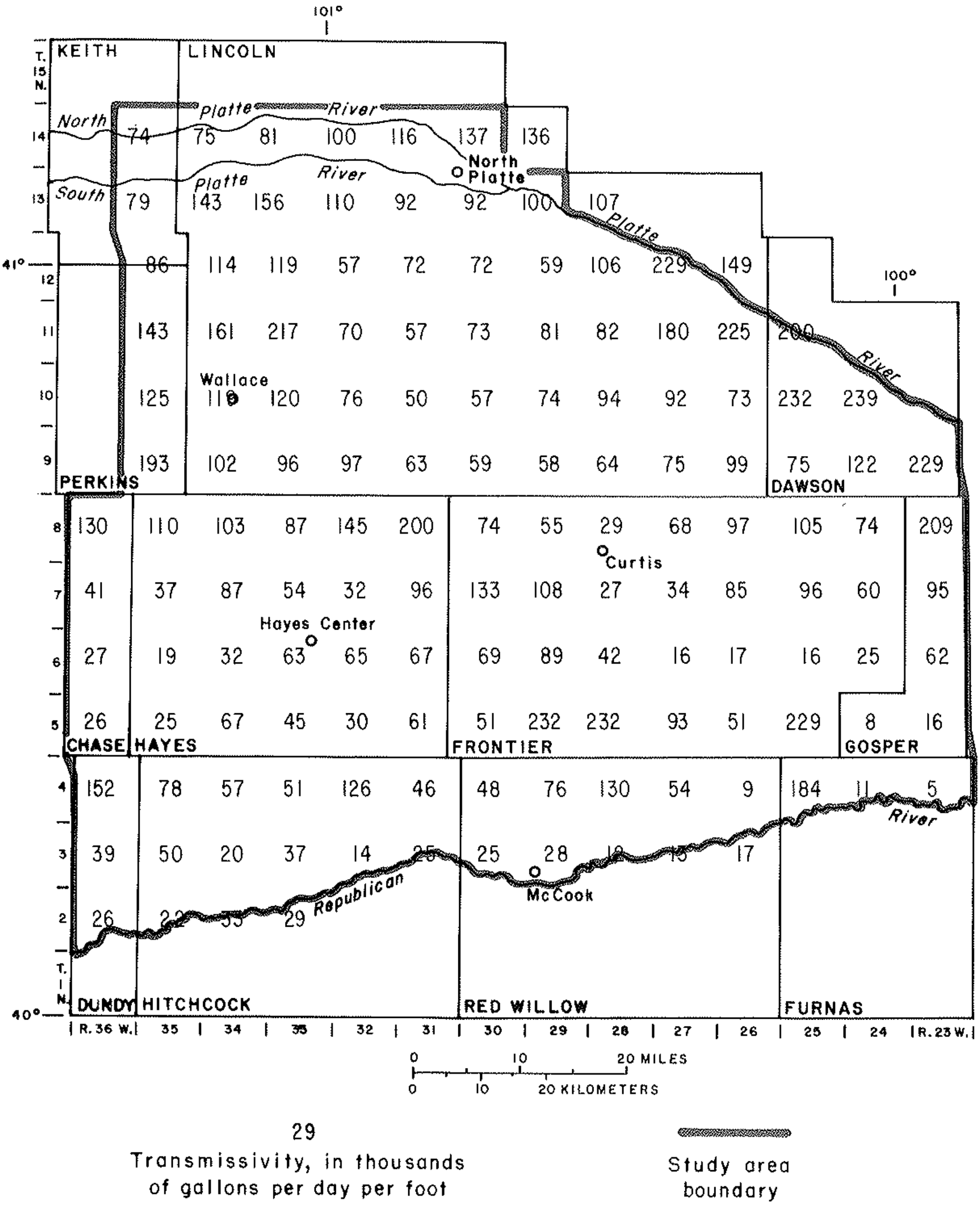


Fig. 36. Adjusted estimated transmissivity values by township.

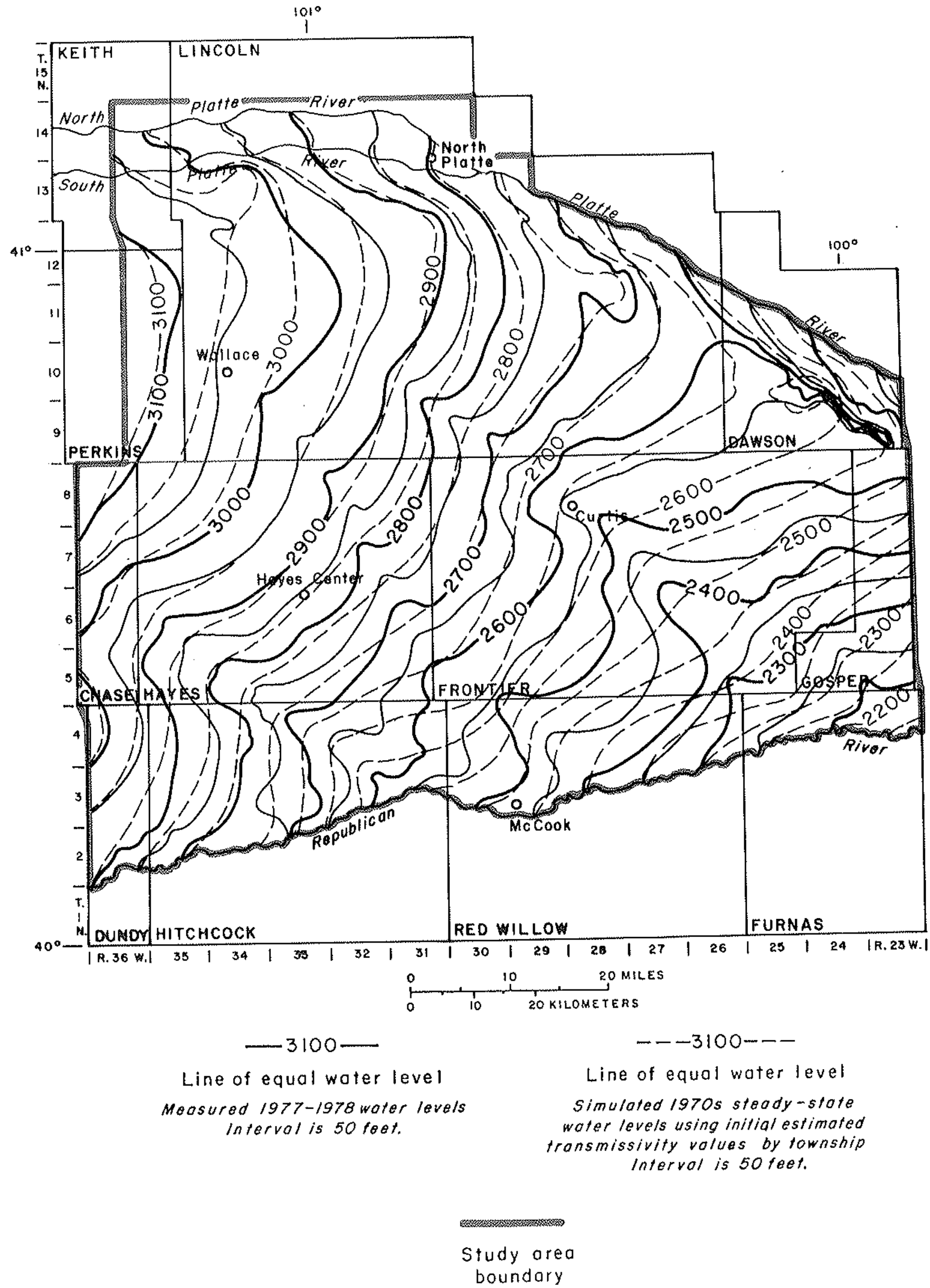


Fig. 37. Simulated 1970s steady-state water levels using initial estimated transmissivity values by township and configuration of the water table, 1977-1978.

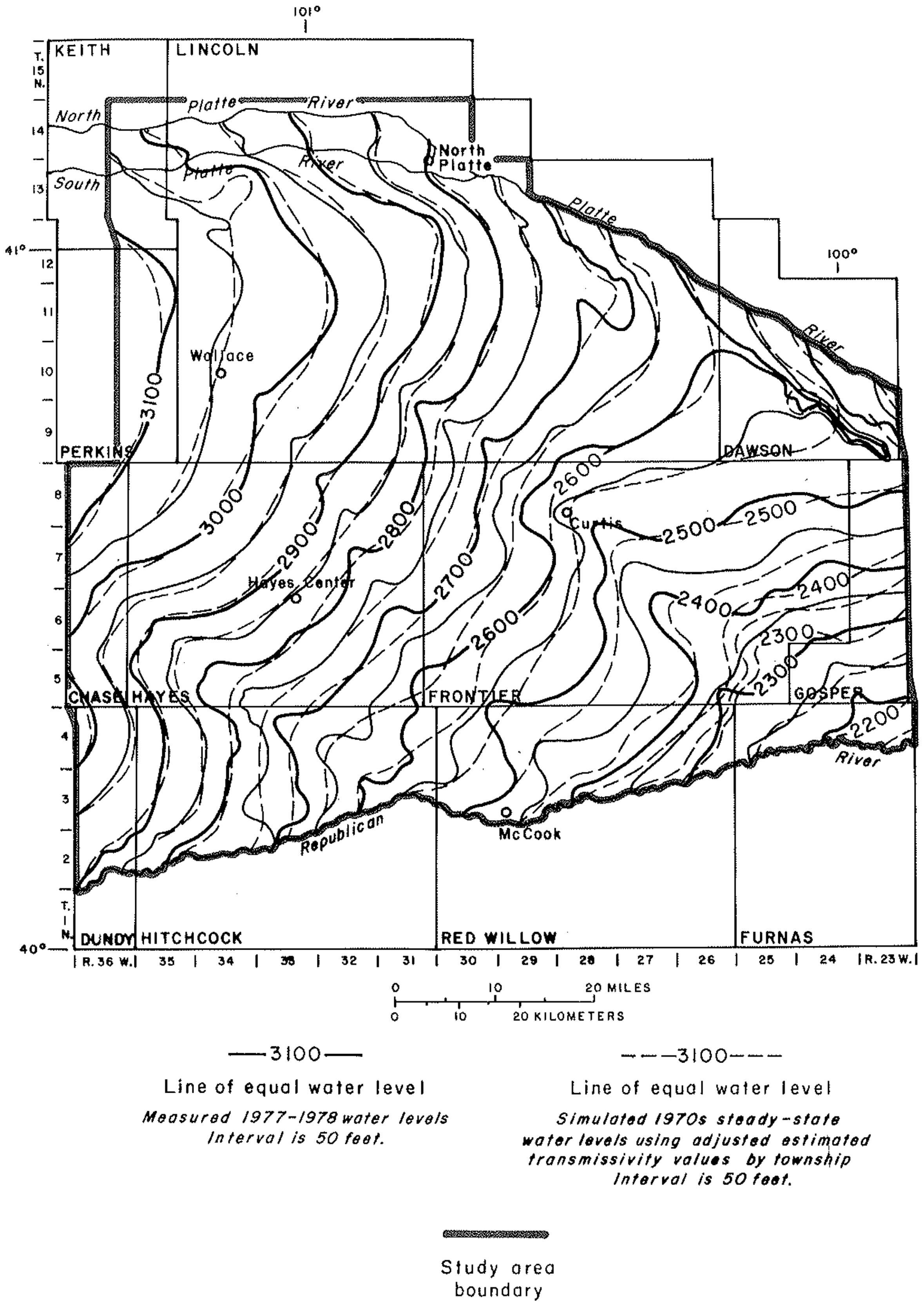


Fig. 38. Simulated 1970s steady-state water levels using adjusted estimated transmissivity values by township and configuration of the water table, 1977-1978.

the observed 1977-1978 water levels (root-mean-square residual of 14 ft).

Figure 39 shows the simulated 1970s steady-state water levels using adjusted estimated transmissivity values by township compared with the same conditions but with the leakage between the stream and the aquifer calculated as a function of the water level in the aquifer and the water level in the stream. The similarity of the two simulations is significant because it indicates the ability of the model to suitably simulate the head distribution in the system using stream-aquifer interaction.

Transient Simulation

Simulating from 1935 to 1978 using the initial estimates of transmissivity resulted in an average water level 12 ft above the observed 1978 level and a root-mean-square residual of 22 ft. The result of simulating from 1935 to 1978 with adjusted township transmissivity values and average estimates of specific yield for each township is represented in figure 40. The average simulated water level is 11 ft above the average observed 1978 water level with a root-mean-square residual of 18 ft. A comparison of figures 40 and 17 is shown in figure 41. It shows a good match between the model's 1978 water levels and the measured 1977-1978 water levels. Specific yield values were not adjusted to achieve a better fit for the transient simulation because of the agreement between the transient simulation (fig. 40) and the steady-state 1970s simulations (fig. 39).

Where possible, simulated streamflows were compared with measured streamflows at gaging stations for both annual and low-flow periods near the end of the calibration period. Average monthly streamflows were used for the measurements, and months with large flows that were caused by precipitation were excluded from the average. Results from this comparison for five sites are listed in table 14. The measured and computed streamflows showed good agreement for most of the sites. Usually, the computed flows were slightly greater than the measured flows. The overall close match between the measured and computed flows indicates that the model is representing the relation between the streams and aquifer adequately.

It also is worth noting that the two major interior streams within the study area, Medicine and Red Willow creeks, were not included in table 14. Medicine Creek lacks a gaging station near its mouth. However, flows in Red Willow Creek, which has a gaging station near its mouth, are affected by unmeasured releases from Hugh Butler Lake and by diversions to the Red Willow Canal.

Results of the comparison of the simulated and measured 1978 water-level maps and of the model and measured streamflows at selected sites indicate a good match between model-generated values and measured values. Therefore, the model calibration for the transient simulation between 1935 and 1978 is adequate for the availability of data and assumptions used.

Mass Balance

An important component of any numerical simulation is the mass balance achieved during the simulation. The numerical consistency of the model often is in part evaluated by examining the mass balance of the model. In essence, the mass balance accounts for the entire amount of water within the groundwater system plus any water entering or leaving the system. For a perfect balance, the amount of water that the system gains or loses over a period should be equal to the difference between the amount of water entering the system and the amount of water leaving the system. A significant error within the mass balance suggests that some component of the hydrogeologic system is not being properly accounted for numerically or that numerical errors within the model are significant.

During the simulation period from 1935 to 1978, the net gain in groundwater storage was 400 billion ft^3 (9.2×10^6 acre-ft) of water. The net recharge or gain to the groundwater system from deep percolation of precipitation and applied irrigation water plus seepage from canals and surface-water impoundments less the total amount of water pumped during this period was 1,250 billion ft^3 of water. However, the net loss of groundwater to streams was estimated at 340 billion ft^3, and known water-level boundary segments, which served as sources and sinks of water during this simulation, amounted to a net discharge or loss of 510 billion ft^3 of water. Thus, the overall balance for the groundwater system is the net gain of 400 billion ft^3 of water.

As previously mentioned, not all of the groundwater in storage is available for withdrawal. Recoverable groundwater in storage within the study area during 1935 is estimated to have been 141 million acre-ft. During 1978 this figure had increased to 145 million acre-ft as a result of seepage from canals and reservoirs in the area. This increase in recoverable groundwater amounts to about 43 percent of the net gain in groundwater storage.

The total error for the groundwater model in the mass balance from 1935 to 1978 was a loss of 2,000 ft^3 water. At considerably less than 0.1 percent of the gain in water stored within the modeled area, the mass balance error is insignificant.

Simulation of Future Conditions

The calibrated groundwater flow model can be used to simulate future hydrogeologic conditions given different development scenarios. However, the accuracy of predicted conditions is related to limitations and uncertainties associated with parameter estimates obtained during model calibration.

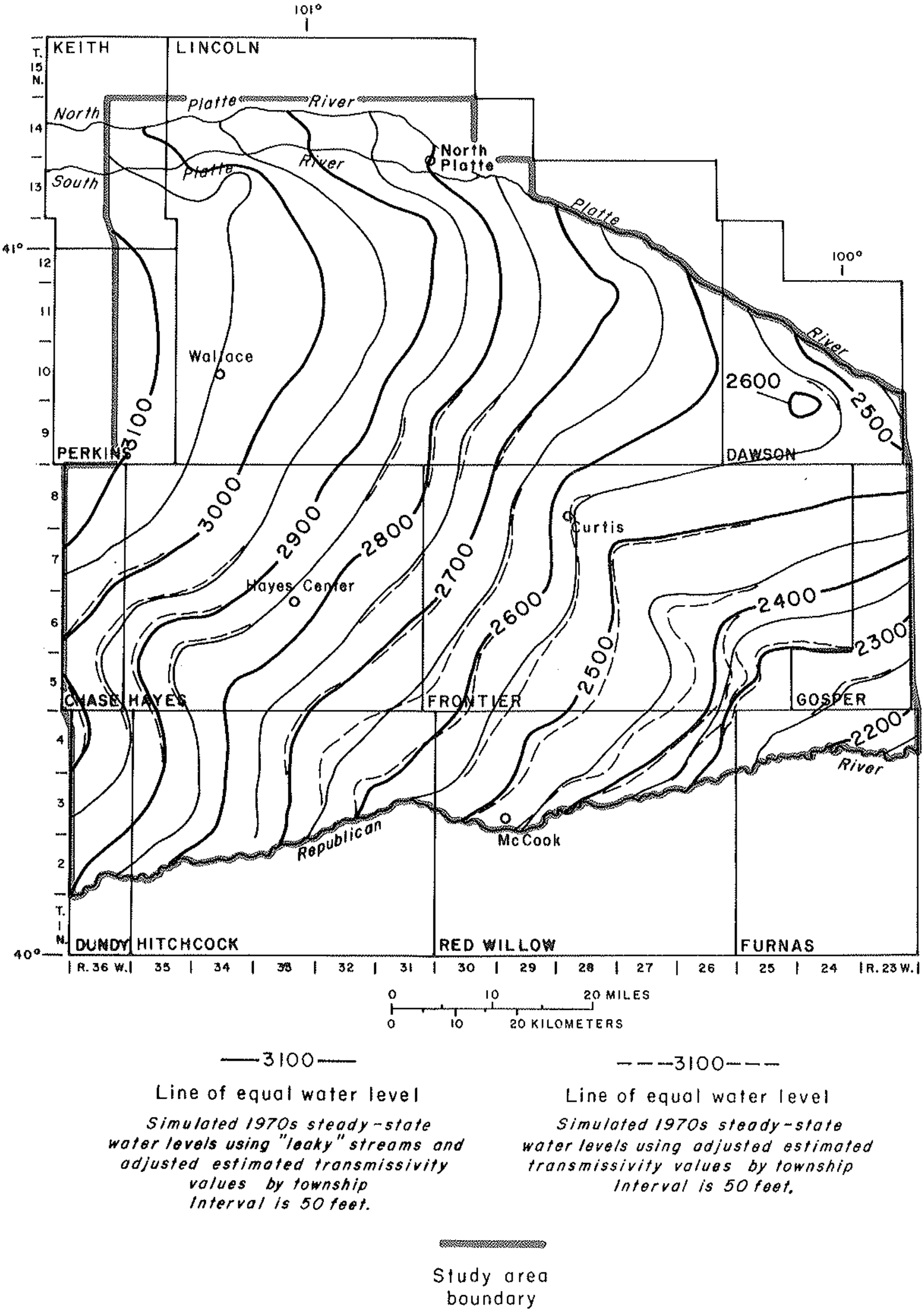


Fig. 39. Simulated 1970s steady-state water levels using adjusted estimated transmissivity values by township with and without "leaky" streams.

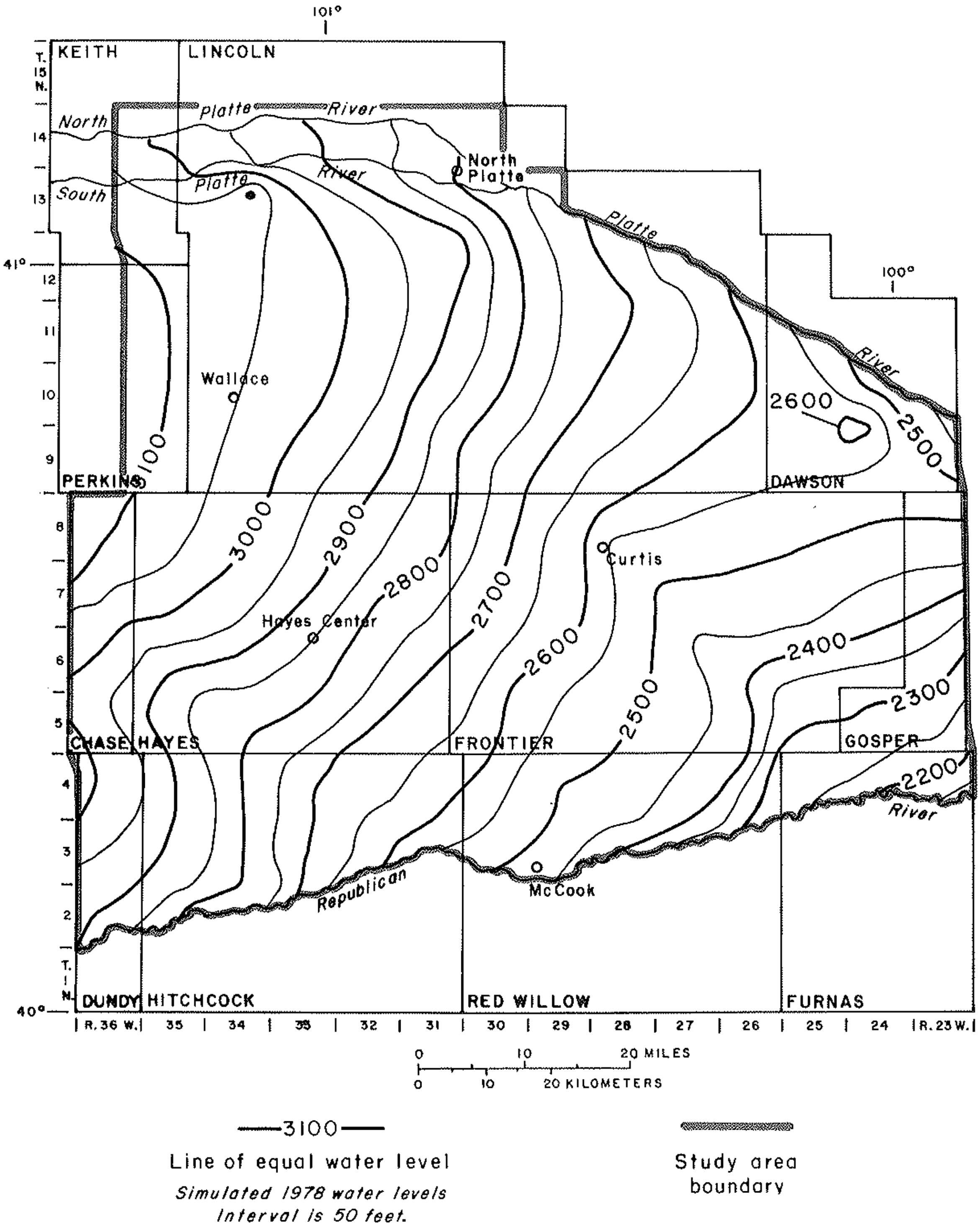


Fig. 40. Simulated 1978 water-level configuration.

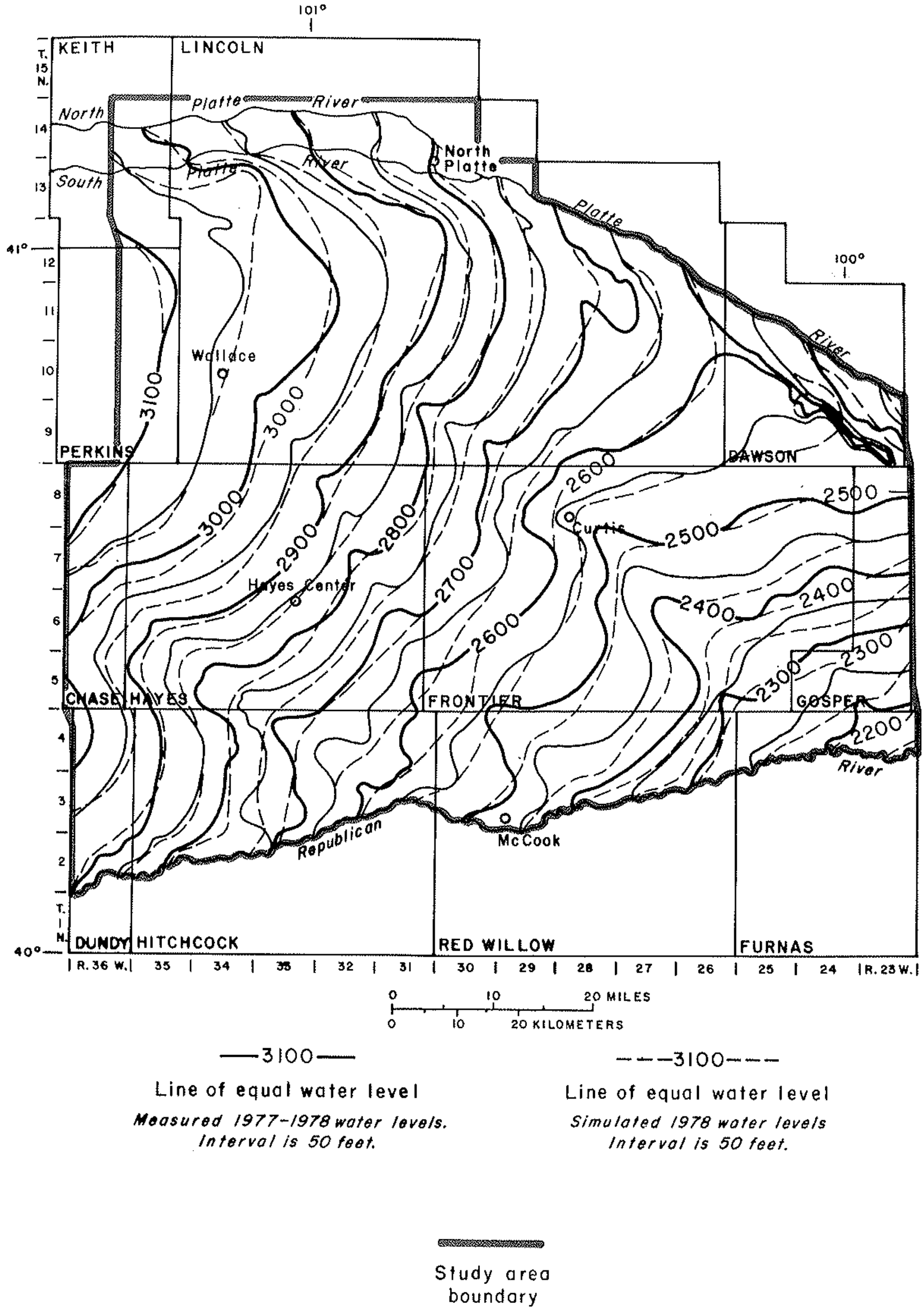


Fig. 41. Simulated 1978 water-level configuration and configuration of the water table, 1977-1978.

Table 14. Measured streamflows, in cubic feet per second, and those computed by the model

U.S. Geological Survey gaging station number and name	September-November average[a] Measured flow	September-November average[a] Computed flow	Annual average[b] Measured flow	Annual average[b] Computed flow
06835000 Stinking Water Creek near Palisade	18.7	19.2	23.8	19.6
06835500 Frenchman Creek at Culbertson	38.2	46.8	40.4	47.8
06836000 Blackwood Creek near	0.9	2.9	2.1	3.1
06840000 Fox Creek at Curtis	3.5	11.3	4.9	11.5
06844000 Muddy Creek at Arapahoe	5.8	5.8	7.2	6.0

[a] Measured values are averaged monthly streamflows for September, October and November, 1980. Months that had large flows caused by precipitation were excluded. Model values are for December 1, 1980; however, these values were developed during the September 2 through December 1, 1980, time period.

[b] Measured values are averaged monthly streamflows from September 1980 through August 1981. Months with large streamflows were excluded from the measured values. Model values were averaged from streamflows on December 1, 1980, and June 1 and September 1, 1981.

Limitations and Potential Uses of Calibrated Groundwater Model

The groundwater model was developed as a regional management tool. Because of the scale of the model, estimates of changes in water levels and streamflows are regional in scope; it should not be implied that they represent the response at individual well sites.

This model was designed to be flexible within the context of a groundwater-simulation model. It was not intended to respond as an optimization model. The model may be used to estimate the response of the groundwater system to specific management decisions, but it is unable to directly estimate the management decision necessary to cause a specific response within the system. For example, it may be used to estimate the result of applying 12 in. of water for 10 yrs, but it will not directly indicate the maximum amount of water that may be pumped so that the groundwater stored in the system will be available for 50 yrs.

Hydrologic conditions at the boundary of the simulated area must be approximated before simulation. Along the east and west boundaries of the modeled area, future conditions were assumed based upon historical conditions. These conditions may or may not be realistic depending upon the future management decisions in the adjoining areas in conjunction with the decisions made within the modeled area. While the model is flexible enough to simulate many hypothetical conditions along these boundaries, these conditions remain approximate at best.

The reliability of the simulation is directly affected by the assumptions, both implied and stated, that were required during all phases of this study exercise. The bulk of the data constituting the basis of the simulation are of necessity speculative because actual measurements of the model's input parameters do not exist.

Streams were simulated from a simplistic viewpoint primarily focused on the interchange of water between the stream and the regional groundwater system. The model makes no attempt to approximate the rainfall-runoff process and as such simulates only the baseflow component of streamflow.

Predictive Scenarios

The calibrated model was extended from 1978 through 1980 so that information from irrigation wells drilled in 1979 and 1980 could be incorporated into the model, and the predictive period was extended from 1980 to 2020. Recharge fluxes for the extension from 1978 through 1980 and for the predictive period were computed by averaging the recharge fluxes from 1963 through 1978. All recoverable groundwater in storage, recharge, and pumpage estimates for 1978 were assumed also to apply to those in 1980.

The calibrated model was used to assess the effect of three irrigation-development scenarios representing minimum development, continued development at the 1970 to 1980 rate, and maximum development. Each scenario was based on a determination of remaining irrigable acres per township as of 1980 and development of those acres to the year 2020 at a rate of 0 percent (minimum development, no new wells after 1980), 2.5 percent per year (continued development), and 10 percent per year (maximum development). Projected percentages of irrigated acreages for the 2.5 and 10 percent annual development rates are listed in table 15. Each development rate was in turn coupled with various amounts of water applied by the wells in place by 1980 or by those added to develop the irrigable acres. Rates of water applied assumed no return to the aquifer and included rates of 6, 9, 12, 15, and 18 in. per year. The assumption of no return of irrigated water to the aquifer was necessary because of a lack of data on specific amounts of water pumped and amounts actually returning to the aquifer. By adding 4 to 5 in. to amounts of water applied, the total inches pumped can be approximated. The application rate of 12 in. per year coupled with the 2.5 percent development rate may provide the most realistic assessment of what might be expected across the area up to the year 2020.

The effects of the development scenarios can be portrayed in a number of ways. Associated with each development rate and amount of water applied, water-

Table 15. Projected percentage of irrigated acreages for selected years for the 2.5 and 10 percent rate of annual groundwater irrigation development

[All values in percent]

County	Irrigable	Irrigated in 1980	Development rate	Projected irrigation 1990	2000	2010	2020
Keith	71	14	2.5	24	34	42	48
			10	49	62	67	68
Perkins	76	11	2.5	26	37	46	52
			10	53	68	73	75
Lincoln	57	14	2.5	22	29	35	40
			10	40	51	55	55
Dawson	68	36	2.5	43	49	54	57
			10	58	65	68	[a]69
Chase	56	12	2.5	22	29	35	40
			10	49	51	54	55
Hayes	64	8	2.5	20	30	38	44
			10	45	57	62	63
Frontier	57	12	2.5	23	30	36	41
			10	41	51	55	56
Gosper	73	16	2.5	29	40	48	54
			10	54	68	72	74
Dundy	63	6	2.5	19	29	37	44
			10	44	58	62	[a]64
Hitchcock	59	18	2.5	27	35	41	45
			10	45	55	58	59
Red Willow	73	27	2.5	37	46	52	56
			10	57	67	71	73
Furnas	71	9	2.5	23	34	43	49
			10	50	64	69	71

[a] Projected irrigation in 2020 exceeds irrigable acres because some acres irrigated in 1980 were not considered irrigable.

level rise or decline maps can be generated to show the magnitude and extent of the rise or decline at various times. For each period, development rate, and amount of water applied, there is a change of water in storage and these changes can be determined (table 16). As water levels rise or fall, baseflow of streams is affected; and for each scenario, the effect on the baseflow is determined. The effect of groundwater development on groundwater discharge to streams is given for two streams considered to represent streams within the study area: Red Willow Creek (table 17) and Medicine Creek (table 18). Finally, any element or point in the study area can be treated as a well, and a hydrograph can be plotted to show the fluctuation of the water table over time at that point.

Minimum Development Scenario

Compared with other predictive scenarios, the minimum development scenario—no additional development—represents the least stress on the groundwater. With no additional development, no new irrigation wells or additional irrigated acres are allowed after 1980 and 6, 9, 12, 15, and 18 in. of water per year is applied. For the 9-in. application rate, water-level rises of 10 ft or more would occur across much of the area by 2020 (fig. 42). The only decline area would be a small area northwest of McCook. Increasing the application rate to 12 in. would reduce the rise areas and extend and increase the severity of the decline to as much as 20 ft northeast of McCook. A new area of decline would appear in southeastern Frontier County by 2020 (fig. 43).

For the 15-in. application rate, the declines through 2020 generally are concentrated just north of the Republican River valley (fig. 44). Overall recharge exceeds discharge for the 6-, 9-, and 12-in. application rates, resulting in water added to storage. By 2020, the additions account for 6.2 million acre-ft, 3.7 million acre-ft, and 1.2 million acre-ft, respectively (table 16). Application rates of 15 and 18 in. would reduce the groundwater in storage by 1.3 million acre-ft and 3.8 million acre-ft, respectively.

By 2020, the groundwater contribution to the streamflow of Red Willow Creek (table 17) is greater than in 1981 for the 6-, 9-, and 12-in. application rates (39.1 percent, 24.8 percent, and 10.2 percent, respectively) and less than in 1981 for the 15- and 18-in. application rates (4.5 percent and 18 percent, respectively). For Medicine Creek, the groundwater contribution to streamflow (table 18) in 2020 also is greater than in 1981 for the 6-, 9-, and 12-in. application rates (27.1 percent, 15.7 percent, and 4.8 percent, respec-

Table 16. Change of groundwater in storage

[in thousands of acre-feet]

Water applied (inch per year)	Development rate (percent)	1985	1990	2000	2010	2020	Percent change 1980 to 2020
6	0	+ 800	+1,700	+ 3,400	+ 4,800	+ 6,200	+ 4.3
9	0	+ 500	+ 900	+ 2,000	+ 2,900	+ 3,700	+ 2.6
12	0	+ 200	+ 300	+ 600	+ 900	+ 1,200	+ .8
15	0	− 200	− 400	− 700	− 1,000	− 1,300	− .9
18	0	− 500	−1,100	− 2,100	− 3,000	− 3,800	− 2.6
6	2.5	+ 600	+ 900	+ 500	− 900	− 3,100	− 2.1
9	2.5	+ 200	− 100	− 2,100	− 5,500	− 9,700	− 6.7
12	2.5	− 200	−1,100	− 4,800	−10,000	−16,400	−11.3
15	2.5	− 600	−2,200	− 7,400	−14,600	−23,100	−15.9
18	2.5	−1,000	−3,200	−10,000	−19,200	−29,800	−20.6
6	10	+ 100	− 800	− 4,300	− 8,500	−13,600	− 9.4
9	10	− 500	−2,600	− 9,100	−16,500	−23,700	−16.3
12	10	−1,100	−4,500	−13,900	−24,500	−34,700	−23.9
15	10	−1,800	−6,300	−18,800	−32,400	−44,600	−30.8
18	10	−2,400	−8,100	−23,600	−39,700	−53,850	−37.1

Table 17. Effects of rate of development on groundwater contribution to streamflow near mouth of Red Willow Creek.

[Average flows in ft³/sec were computed from model-generated flows on September 1 and December 1 of appropriate year]

Water applied (inches per year)	Development rate (percent)	1981 average flow[a]	1990 average flow	Percent change 1981-1990	2000 average flow	Percent change 1981-2000	2010 average flow	Percent change 1981-2010	2020 average flow	Percent change 1981-2020
6	0	26.6	29.8	+12.0	32.5	+22.2	34.9	+ 31.2	37.0	+ 39.1
9	0	26.6	28.7	+ 7.9	30.4	+14.3	31.9	+ 19.9	33.2	+ 24.8
12	0	26.6	27.6	+ 3.8	28.3	+ 6.4	28.9	+ 8.7	29.3	+ 10.2
15	0	26.6	26.5	− .38	26.2	− 1.5	25.8	− 3.0	25.4	− 4.5
18	0	26.6	25.4	− 4.5	24.1	− 9.4	22.9	− 13.9	21.8	− 18.0
6	2.5	26.6	28.3	+ 6.4	27.2	2.3	24.4	− 8.3	20.7	− 22.2
9	2.5	26.6	26.5	− .38	22.8	−14.3	17.1	− 35.7	10.8	− 59.4
12	2.5	26.6	24.7	− 7.1	18.6	−30.1	10.4	− 60.9	4.4	− 83.5
15	2.5	26.6	22.9	−13.9	14.5	−45.5	5.4	− 79.7	0.8	− 97.0
18	2.5	26.6	21.2	−20.3	10.6	−60.2	2.2	− 91.7	0.0	−100.0
6	10	26.6	24.8	− 6.8	18.6	−30.1	12.0	− 54.9	7.8	− 70.7
9	10	26.6	21.6	−18.8	11.2	−57.9	4.8	− 82.0	1.9	− 92.2
12	10	26.6	18.4	−30.8	5.9	−77.8	0.88	− 96.7	0.0	−100.0
15	10	26.6	15.4	−42.1	2.8	−89.5	0.0	−100.0	0.0	−100.0
18	10	26.6	12.6	−52.6	.39	−98.5	0.0	−100.0	0.0	−100.0

[a] Application rate and development rate for the 1981 average flow was 100 percent consumptive irrigation requirement and "0" development rate, respectively.

tively) and less than in 1981 for the 15- and 18-in. application rates (5.4 percent and 17.4 percent, respectively).

Maximum Development Scenario

The maximum development scenario consists of developing 10 percent of the irrigable but non-irrigated acres each year. This scenario develops most areas quickly. By the year 2000, an application rate of 9 in. coupled with 10-percent development would produce declines of 10 to 20 ft across much of the area (fig. 45). Greater declines will occur by the year 2000 for larger application rates; 20- to 30-ft declines will be common for the 12-in. application rate (fig. 46), and declines of 40 to 60 ft are common for the 15-in. ap-

Table 18. Effects of rate of development on groundwater contribution to streamflow near mouth of Medicine Creek.

[Average flows were computed from model-generated flows on September 1 and December 1 of appropriate year]

Water applied (inches per year)	Development rate (percent)	1981 average flow[a]	1990 average flow	Percent change 1981-1990	2000 average flow	Percent change 1981-2000	2010 average flow	Percent change 1981-2010	2020 average flow	Percent change 1981-2020
6	0	65.0	71.0	+ 9.2	75.1	+15.5	79.2	+21.8	82.6	+27.1
9	0	65.0	68.4	+ 5.2	70.5	+ 8.5	73.4	+12.9	75.2	+15.7
12	0	65.0	65.7	+ 1.1	66.4	+ 2.2	66.8	+ 2.8	68.1	+ 4.8
15	0	65.0	63.1	− 2.9	62.1	− 4.5	61.5	− 5.4	61.5	− 5.4
18	0	65.0	60.4	− 7.1	57.6	−11.4	55.5	−14.6	53.7	−17.4
6	2.5	65.0	67.4	+ 3.7	63.6	− 2.2	58.4	−10.2	51.4	−20.9
9	2.5	65.0	63.3	− 2.6	55.0	−15.4	42.8	−34.2	30.4	−53.2
12	2.5	65.0	59.2	− 8.9	45.8	−29.5	28.3	−56.5	13.6	−79.1
15	2.5	65.0	55.2	−15.1	36.0	−44.6	15.6	−76.0	2.0	−96.9
18	2.5	65.0	51.5	−20.8	27.6	−57.5	6.2	−90.5	0.0	100
6	10	65.0	59.9	− 7.8	45.9	−29.4	32.7	−49.7	22.6	−65.2
9	10	65.0	52.5	−19.2	29.4	−54.8	11.1	−82.9	2.2	−96.6
12	10	65.0	45.1	−30.6	14.4	−77.8	0.44	−99.3	0.0	100
15	10	65.0	37.8	−41.8	4.5	−93.1	0.0	100	0.0	100
18	10	65.0	30.8	−52.6	0.49	−99.2	0.0	100	0.0	100

[a] Application rate and development rate for the 1981 average flow was 100 percent consumptive irrigation requirement and "0" development rate, respectively.

plication rate (fig. 47). By the year 2020, a 12-in. application rate and a 10-percent development rate produce declines greater than 60 ft throughout much of the study area, with a maximum decline of 140 ft (fig. 48).

Groundwater in storage in 2020 would be reduced by 13.6 million acre-ft under a 6-in. application rate, 23.7 million acre-ft for a 9-in. application rate, 34.7 million acre-ft for a 12-in. application rate, 44.6 million acre-ft for a 15-in. application rate, and 53.8 million acre-ft for an 18-in. application rate (table 16).

By 2020, the groundwater contribution to the streamflow of Red Willow Creek (table 17) is less than in 1981 for the 6- and 9-in. application rates (70.7 percent and 92.2 percent, respectively) while the groundwater contribution is non-existent at the larger application rates. Similarly, for Medicine Creek, the groundwater contribution to streamflow (table 18) in 2020 is less than in 1981 for the 6- and 9-in. application rates (65.2 percent and 96.6 percent, respectively) and non-existent at the 12-, 15-, and 18-in. applications.

Continued Development Scenario

From 1970 to 1980, the average development of irrigable acres across the study area was approximately 2.5 percent per year. Projecting this development rate to the year 2020 possibly provides the most realistic assessment of the immediate future of the groundwater reserves in the area. Water-level changes by the year 2000 that would be associated with 9-, 12-, and 15-in. application rates at a development rate of 2.5 percent are shown in figures 49 through 51. Declines on the order of 10 ft generally are concentrated near the Republican River valley (fig. 49) with an application rate of 9 in. The application of 12 in., being approximately equal to 16 in. of water pumped (assuming 4 in. is recharged to the aquifer), provides a reasonable estimate of use combined with a realistic development rate. The 12-in. application rate expands the 10-ft decline area considerably and some 20-ft declines appear in the Republican River valley (fig. 50). Declines of 10 to 20 ft will be common over much of the study area by the year 2000 (fig. 51) for an application rate of 15 in. By the year 2020, a 12-in. application rate (fig. 52) produces declines of 20 to 40 ft over much of the study area.

Groundwater in storage in 2020 would be reduced by 3.1 million acre-ft for a 6-in. application rate, 9.7 million acre-ft for a 9-in. application rate, 16.4 million acre-ft for a 12-in. application rate, 23.1 million acre-ft for a 15-in. application rate, and 29.8 million acre-ft for an 18-in. application rate (table 16).

By 2020, the groundwater contribution to the streamflow of Red Willow Creek (table 17) is less than in 1981 for the 6-, 9-, 12-, and 15-in. application rates (22.2 percent, 59.4 percent, 83.5 percent, and 97 percent, respectively) while the groundwater contribution is nonexistent at the 18-in. application rate. Similarly, for Medicine Creek, the groundwater contribution to streamflow (table 18) in 2020 is less than in 1981 for the 6-, 9-, 12-, and 15-in. application rates (20.9 percent, 53.2 percent, 79.1 percent, and 96.9 percent, respectively) and nonexistent at the 18-in. application rate.

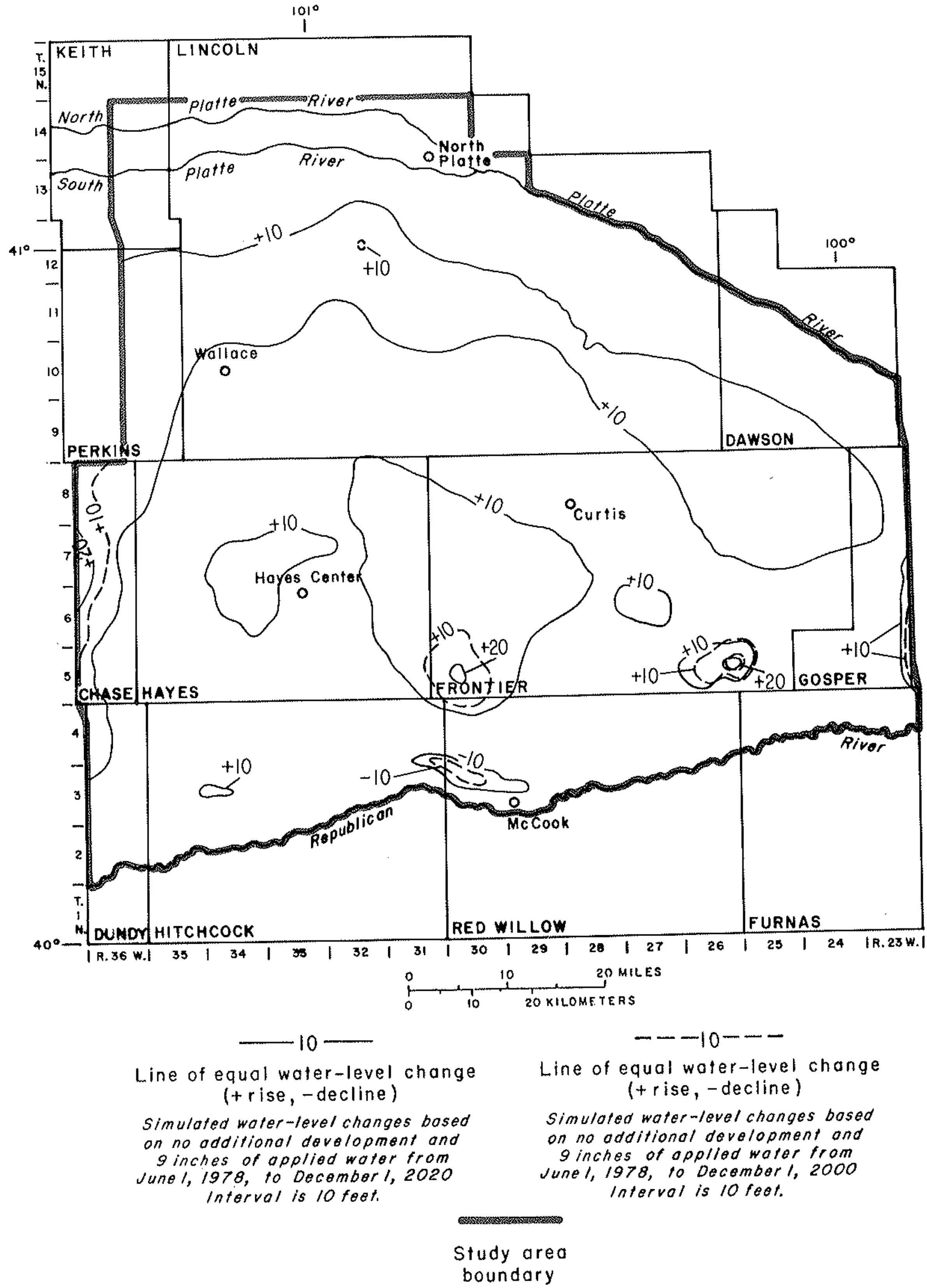


Fig. 42. Simulated water-level changes by the years 2000 and 2020 with no additional development and 9 in. of irrigation water applied.

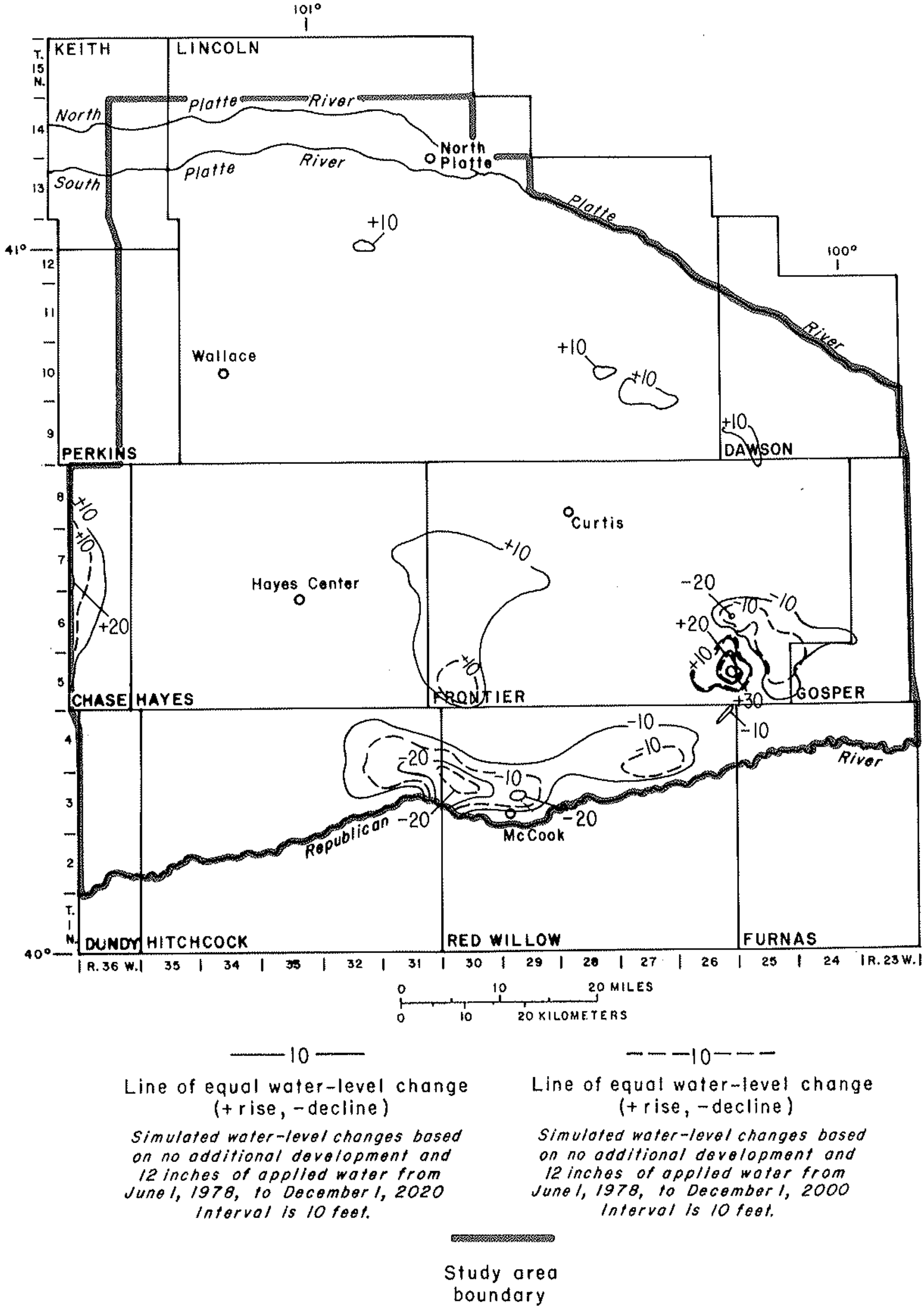
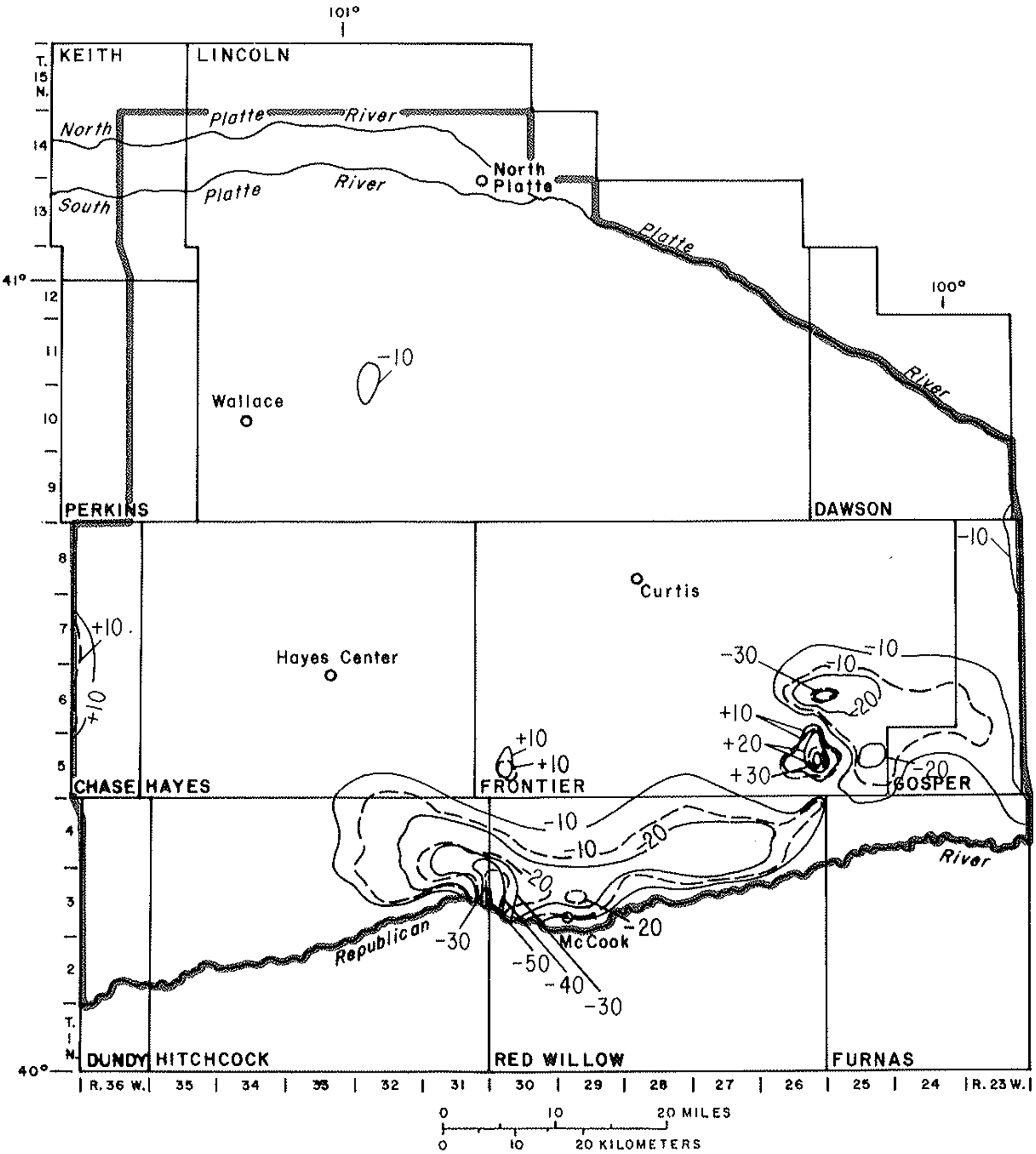


Fig. 43. Simulated water-level changes by the years 2000 and 2020 with no additional development and 12 in. of irrigation water applied.



—— 10 ——
Line of equal water-level change (+ rise, − decline)
Simulated water-level changes based on no additional development and 15 inches of applied water from June 1, 1978, to December 1, 2020 Interval is 10 feet.

– – – 10 – – –
Line of equal water-level change (+ rise, − decline)
Simulated water-level changes based on no additional development and 15 inches of applied water from June 1, 1978, to December 1, 2000 Interval is 10 feet.

Study area boundary

Fig. 44. Simulated water-level changes by the years 2000 and 2020 with no additional development and 15 in. of irrigation water applied.

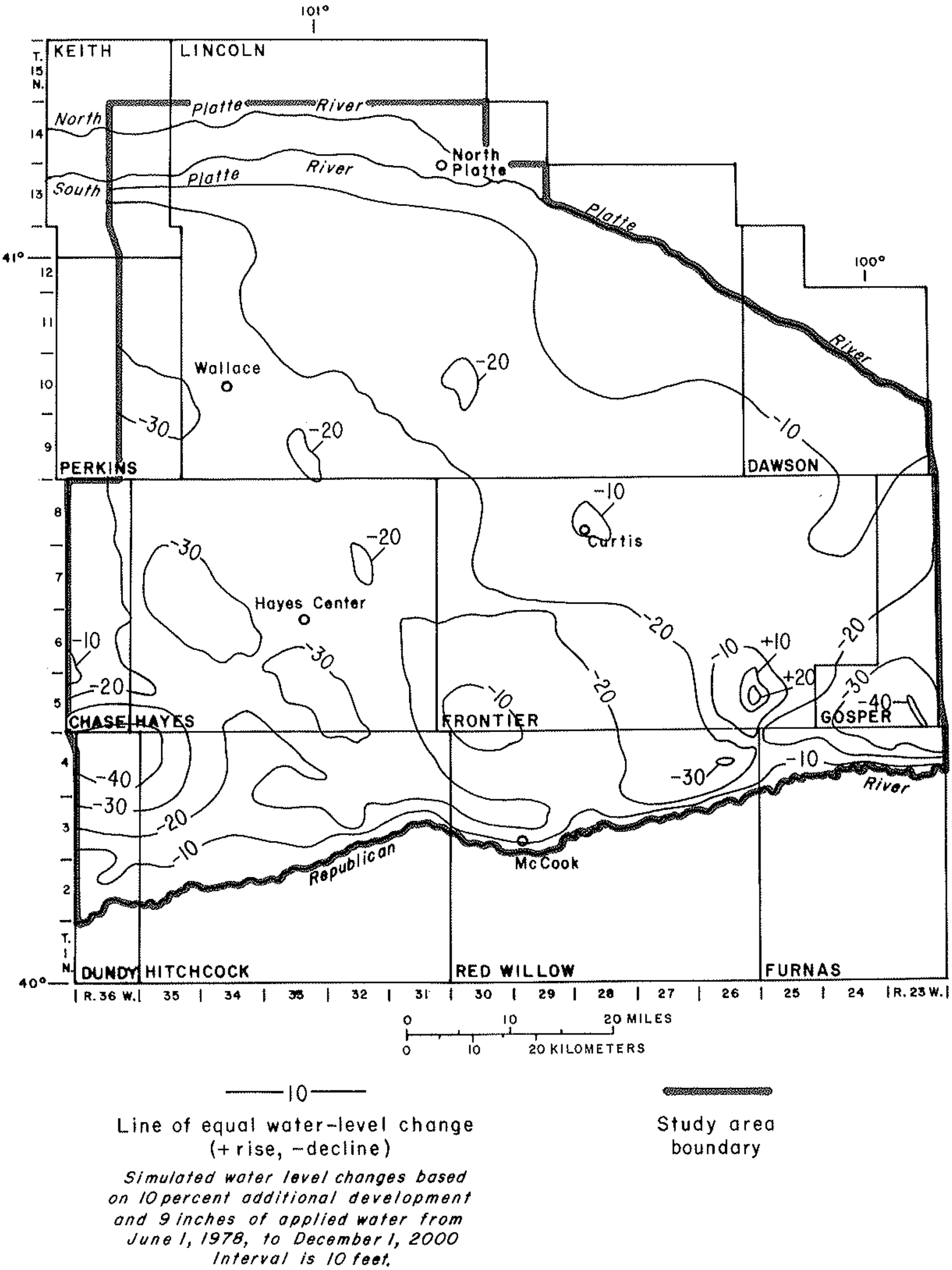


Fig. 45. Simulated water-level changes by the year 2000 with 10 percent additional development and 9 in. of irrigation water applied.

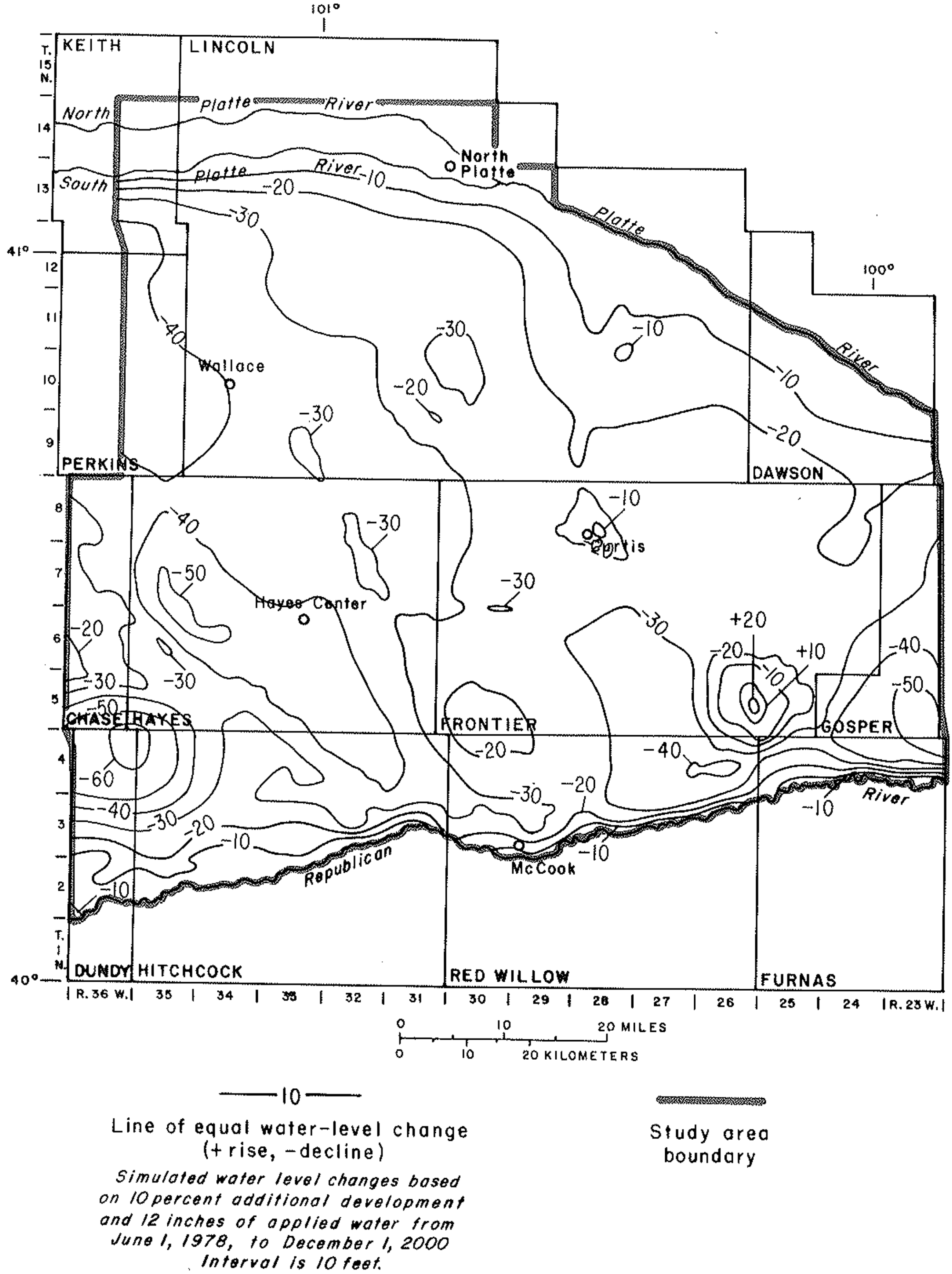


Fig. 46. Simulated water-level changes by the year 2000 with 10 percent additional development and 12 in. of irrigation water applied.

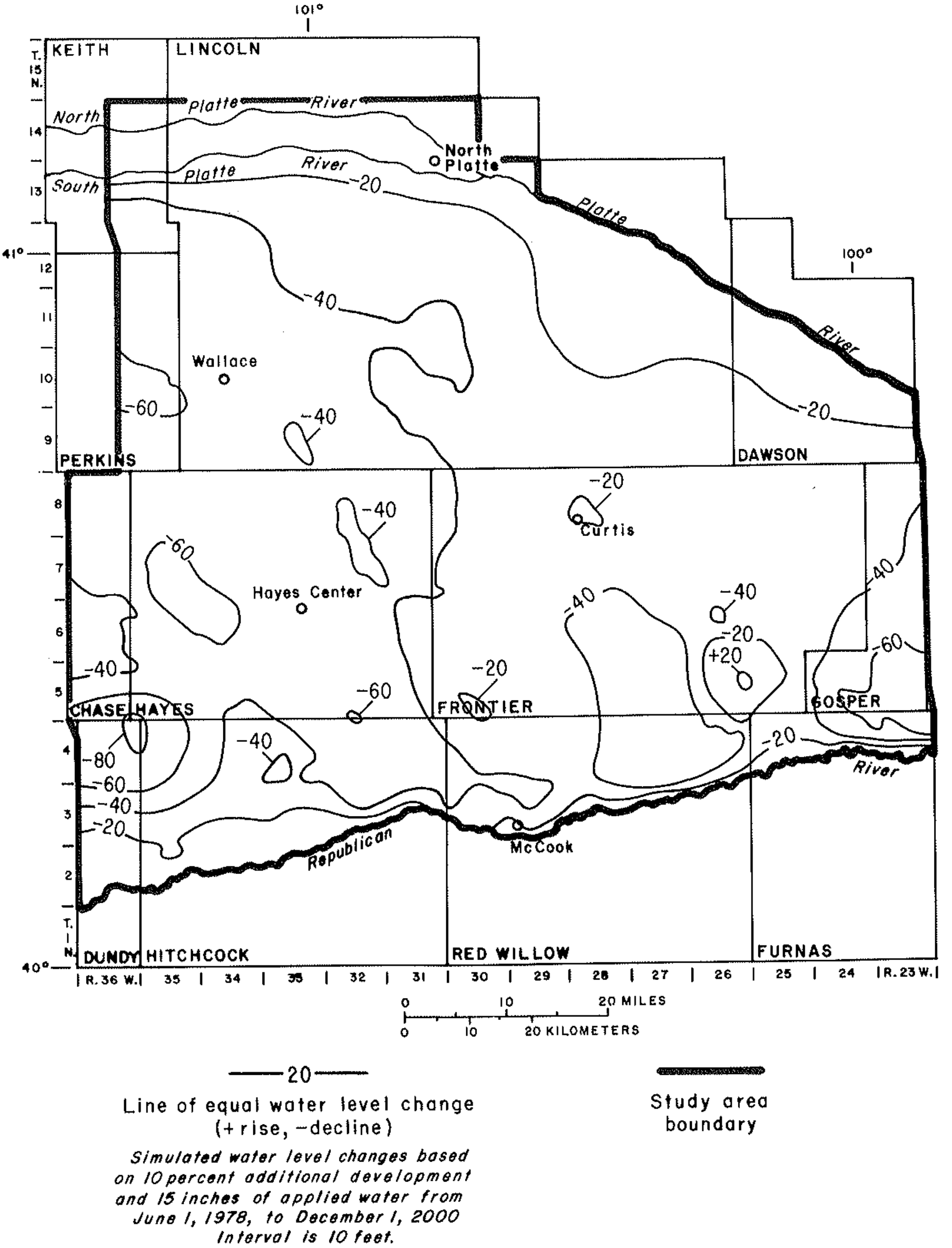


Fig. 47. Simulated water-level changes by the year 2000 with 10 percent additional development and 15 in. of irrigation water applied.

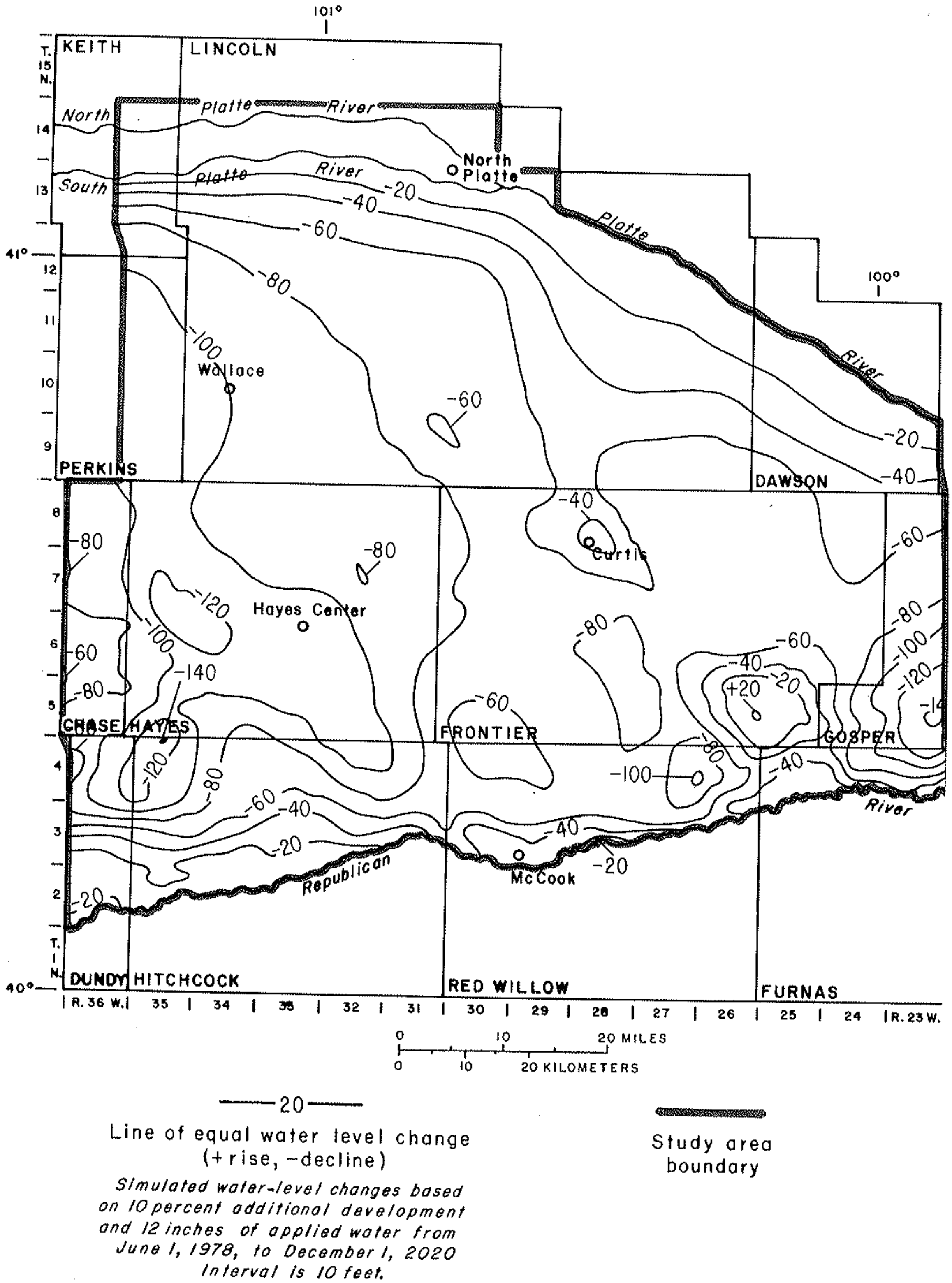


Fig. 48. Simulated water-level changes by the year 2020 with 10 percent additional development and 12 in. of irrigation water applied.

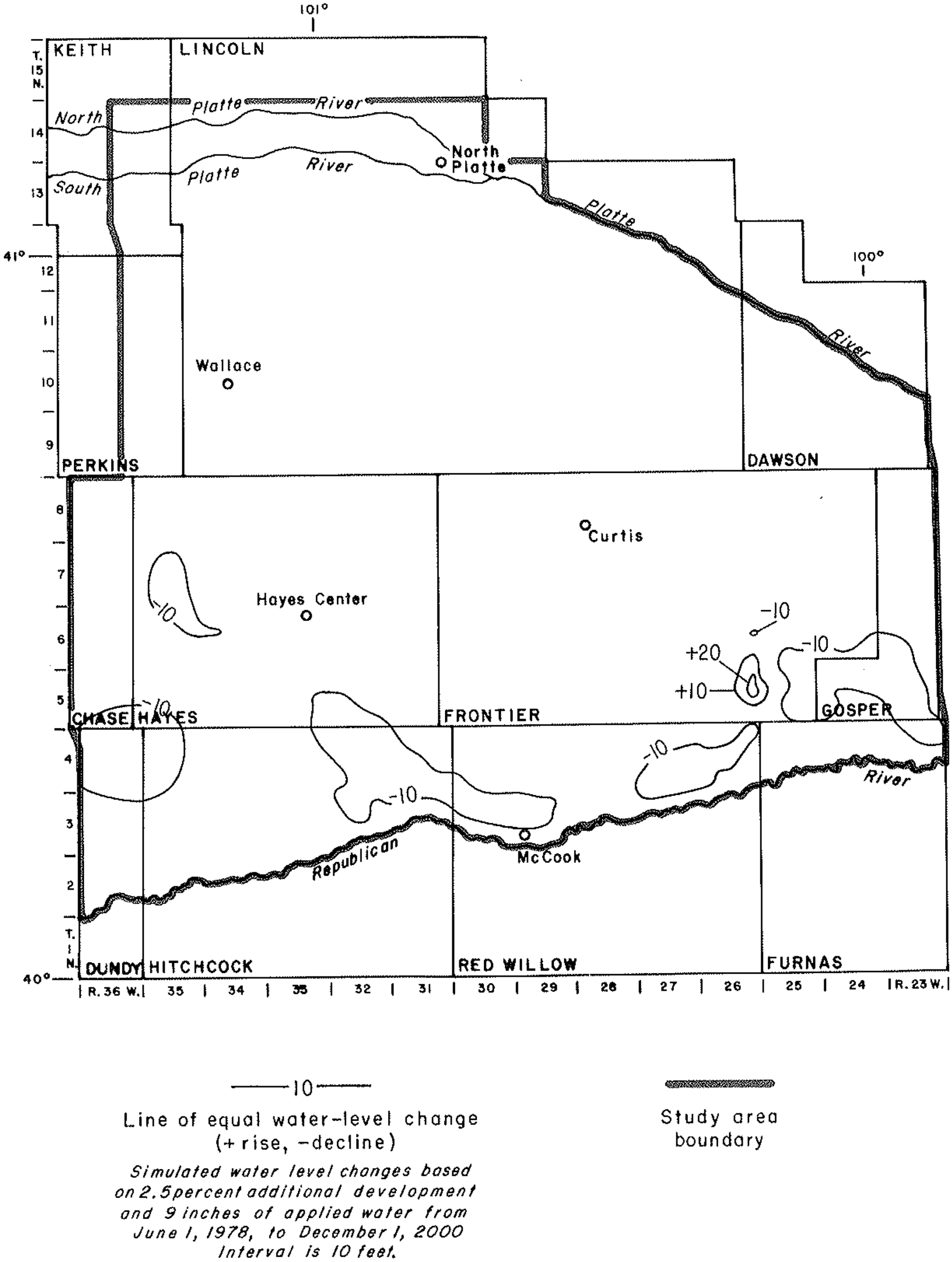


Fig. 49. Simulated water-level changes by the year 2000 with 2.5 percent additional development and 9 in. of irrigation water applied.

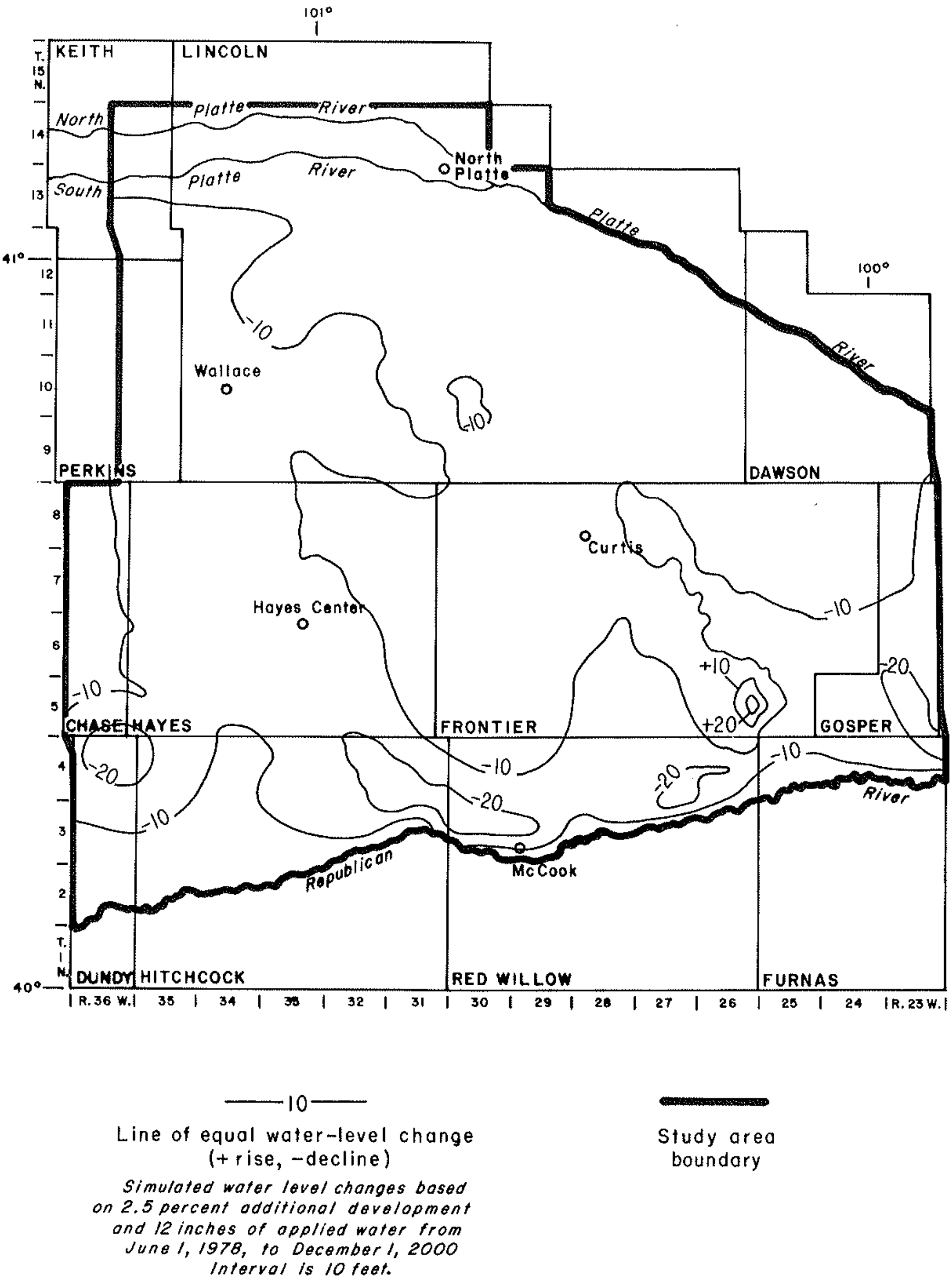


Fig. 50. Simulated water-level changes by the year 2000 with 2.5 percent additional development and 12 in. of irrigation water applied.

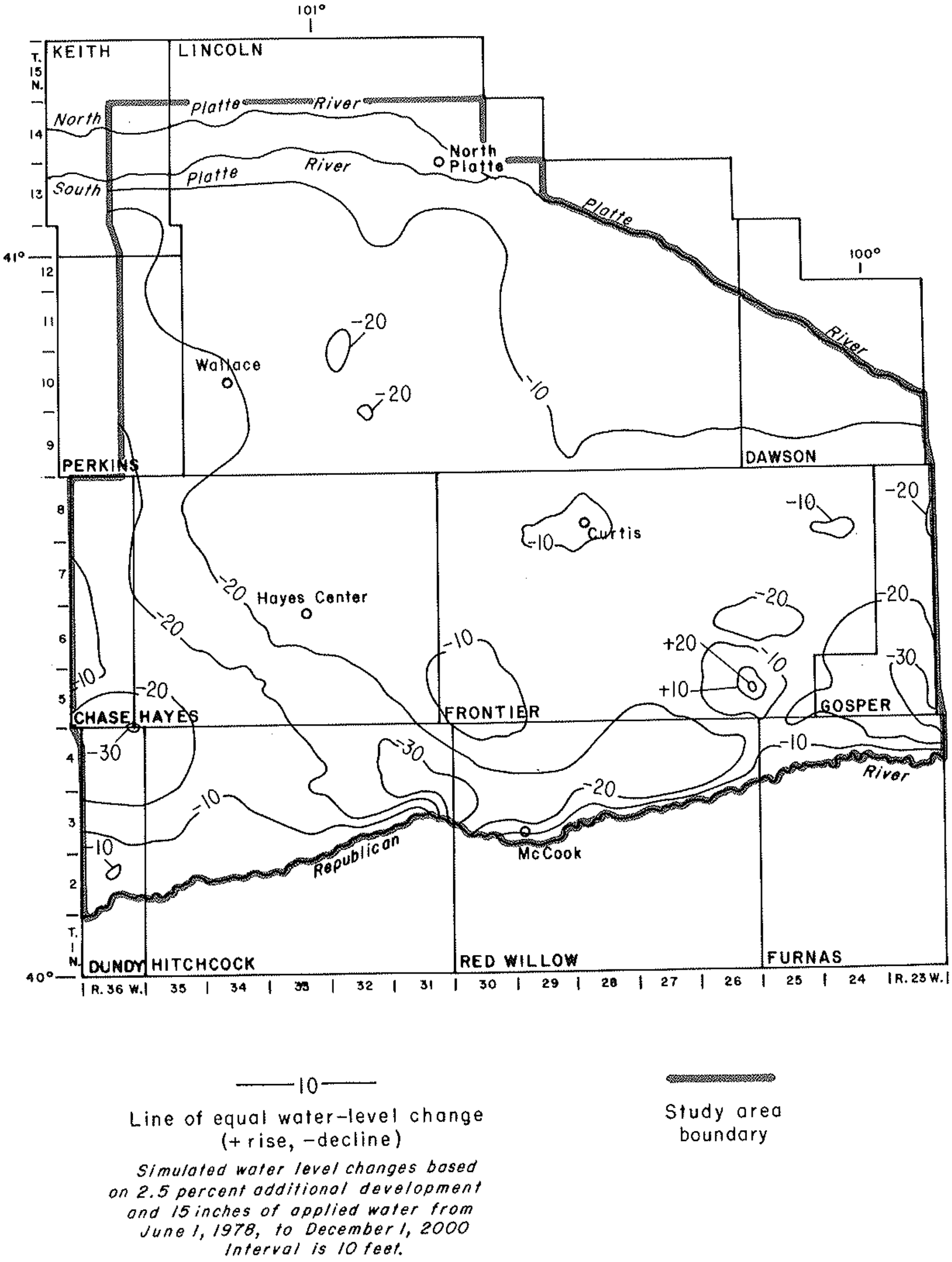


Fig. 51. Simulated water-level changes by the year 2000 with 2.5 percent additional development and 15 in. of irrigation water applied.

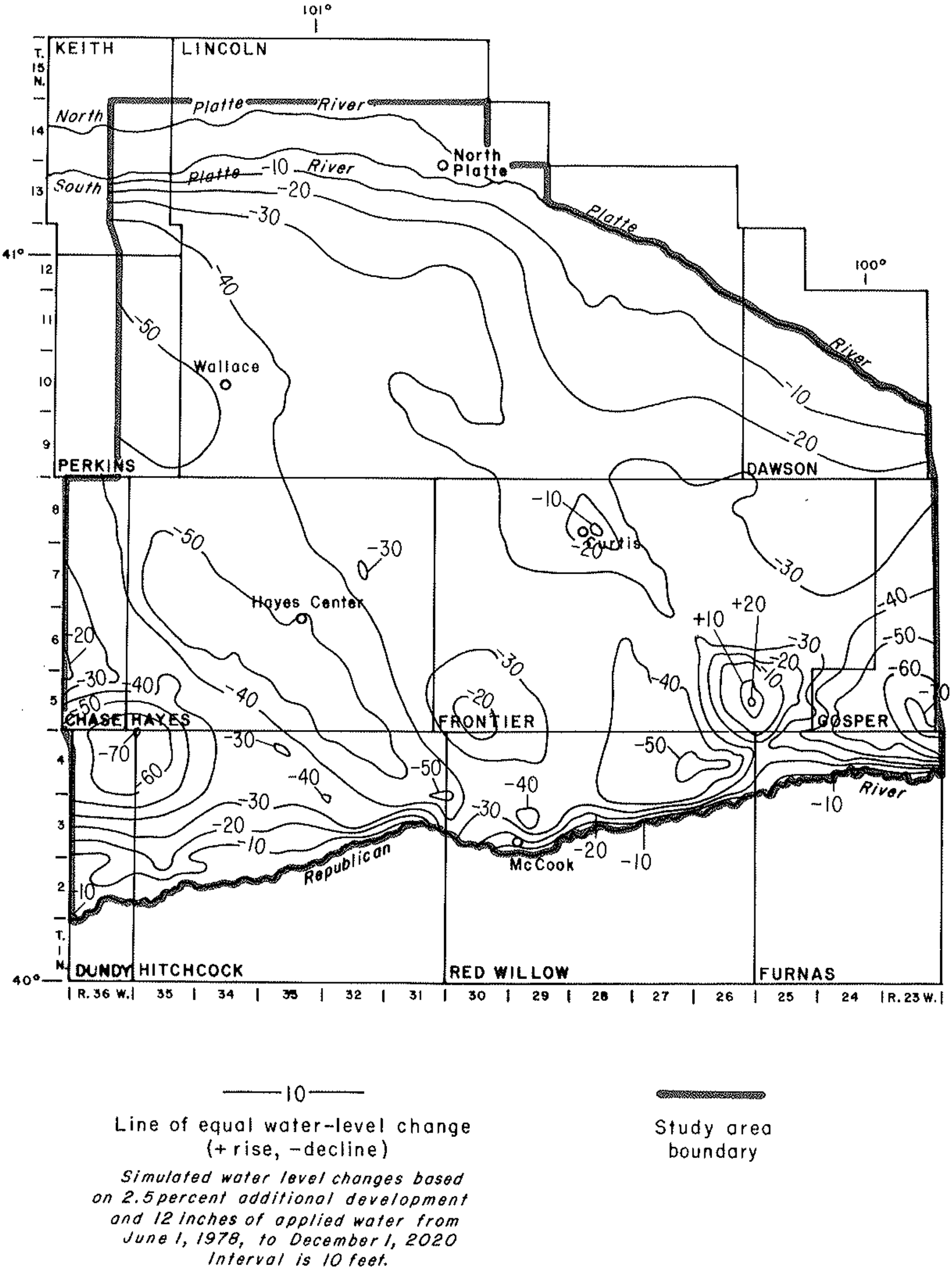


Fig. 52. Simulated water-level changes by the year 2020 with 2.5 percent additional development and 12 in. of irrigation water applied.

Summary

The hydrogeologic system in the Twin Platte and Middle Republican NRDs in southwestern Nebraska receives groundwater inflow from the four counties to the west, from precipitation on the study area, and from canal and reservoir seepage. Surface-water inflow comes from the North and South Platte rivers, Stinking Water Creek, Frenchman Creek, and the Republican River. Outflow consists of consumptive use of soil moisture and groundwater, streamflow and canal flow in the Platte River and Republican River valleys, and groundwater underflow across the eastern boundary of the study area. Before 1935, inflow is assumed to have been balanced by outflow.

The water quality in the study area was evaluated by collecting and analyzing water samples from 20 observation wells during 1977 and 1978 and from 99 irrigation wells during 1979. Calcium was the principal anion. The sources of these ions are the Quaternary deposits and the Ogallala Group.

The specific conductance of water samples increased approximately 40 percent in the uplands from west to east across the study area. However, in the valleys along the northern and southern borders of the study area, the specific conductance of the water samples was higher than those in the uplands. This probably was caused by highly mineralized waters seeping from the rivers and canals. Groundwater in the valleys contains concentrations of sodium and sulfate approaching those of calcium and bicarbonate.

The groundwater was determined to be both suitable for human and irrigation uses across the study area. Two water samples exceeded the MCL for nitrate as N; however, these represented only local problems with no regional significance.

Recoverable groundwater in storage within the study area during 1935 is estimated to have been 141 million acre-ft. During 1978 this figure had increased to 145 million acre-ft as a result of seepage from canals and reservoirs in the area. Annual recharge from precipitation during 1978 was estimated at 222,300 acre-ft, while pumpage of groundwater was estimated at 240,000 acre-ft.

A soil-zone model and recharge-discharge model were used to estimate fluxes, and these data were used in a finite-element groundwater flow model (RAQSIM) of the saturated zone to simulate the hydrogeologic system. The modeled response of the hydrogeologic system between predevelopment (1935) and recent irrigation development (1978) was compared to estimates of predevelopment conditions and measured 1978 conditions. Differences between measured and computed hydrogeologic responses were resolved to acceptable levels through a calibration process. The calibrated model was then used to assess the effects to the year 2020 on water levels and streamflows of three development scenarios representing minimum development, continued development at the 1970 to 1980 rate, and maximum development rates, each coupled with a range of applied irrigation water.

The minimum-development scenario of no additional development or no new irrigated acres after 1980, coupled with application rates of 6, 9, and 12 in. per year, would result in a net increase of groundwater in storage and an increase in baseflow of streams. Despite the increase in net storage with a 12-in. application rate, there would be areas of water-level decline of from 10 to 20 ft by 2020 from northeastern Hitchcock County across Red Willow County and in southeastern Frontier County where the saturated thickness of the aquifer is 100 ft or less. Application rates of 15 and 18 in. and no additional development would decrease available water in storage, diminish groundwater contribution to streamflow, and cause water-level declines of 10 to 20 ft over most of the study area.

The 12-in. application rate combined with the 2.5-percent development rate most closely approximates what might be anticipated and shows reductions in storage of 16.4 million acre-ft by 2020. Compared to the 145 million acre-ft of recoverable groundwater during 1980, the 2020 figure is a decrease of 11.3 percent. The 11.3 percent decrease in storage would also be reflected by a loss of approximately 80 percent of the 1981 average baseflow in Medicine and Red Willow creeks. Average regional water levels would decline 20 to 40 ft by 2020.

The maximum development rate of 10 percent, coupled with any of the irrigation application rates, would by 2000 greatly increase water-level declines, reduce storage, and diminish streamflow. Combining the 12 in. per year application rate with the 10-percent development would create average declines greater than 60 ft throughout much of the study area by 2020 and reduce the total water in storage by approximately 24 percent. Also, streamflow in Medicine and Red Willow creeks derived from groundwater would essentially disappear by 2020 for this combination of application and development.

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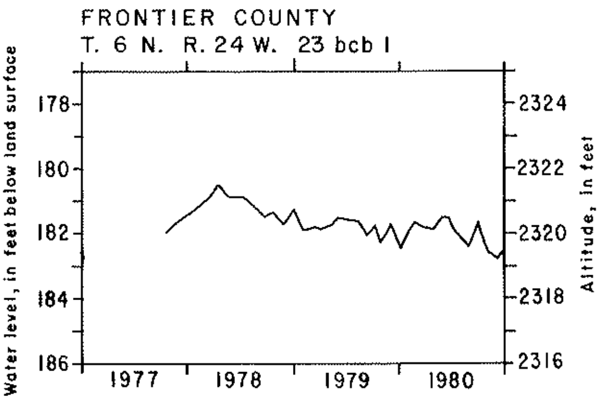
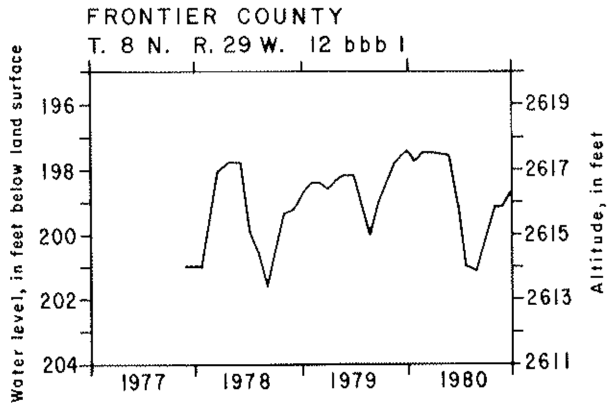
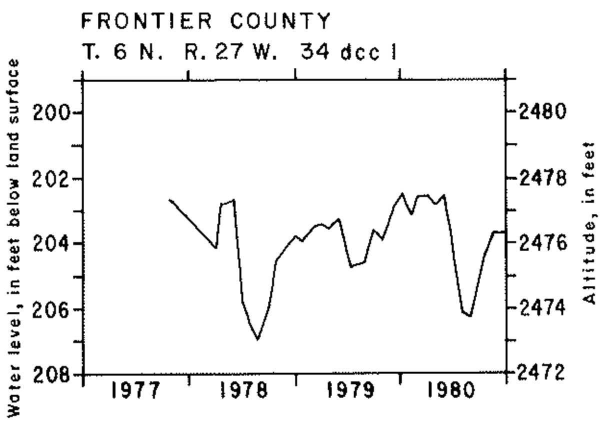
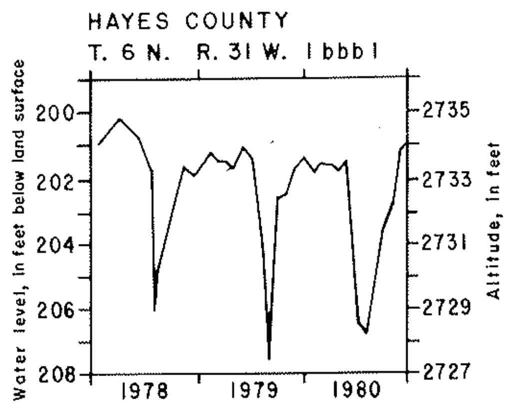
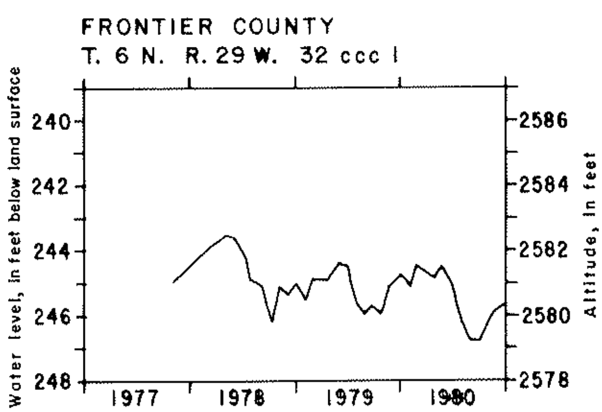
Appendix A. Hydrographs from observation wells measured monthly.

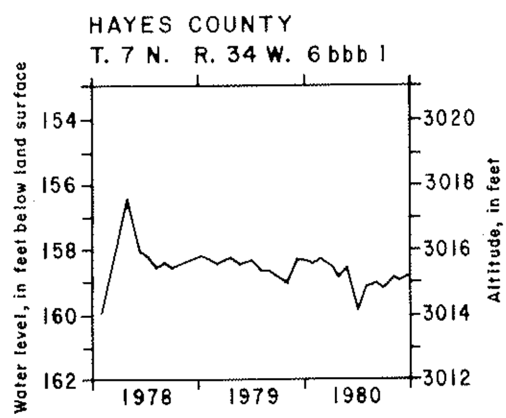


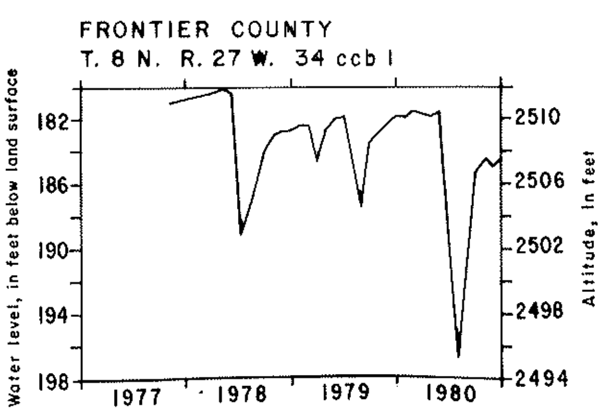


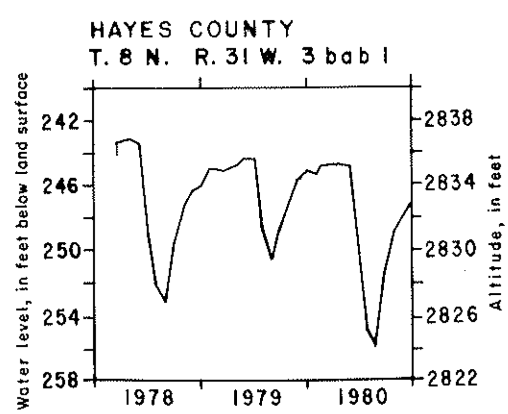




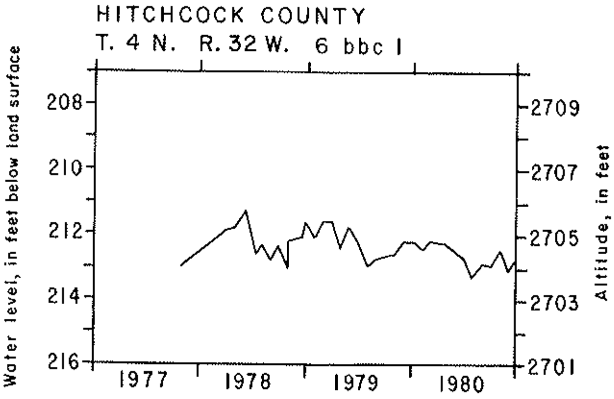


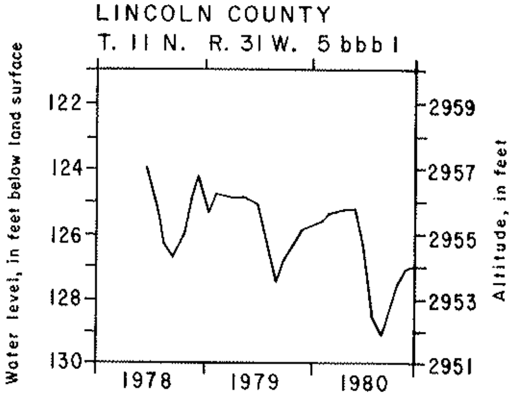


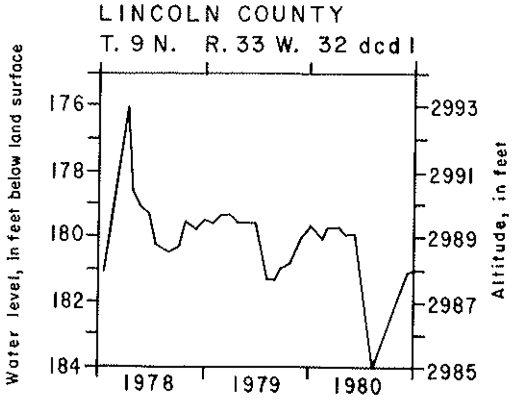


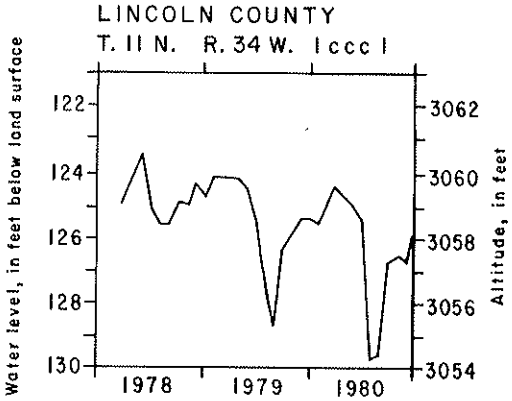


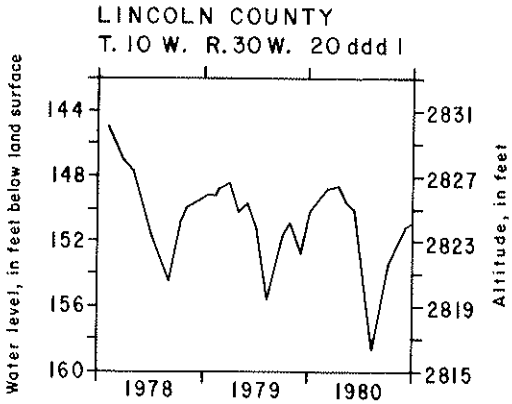
Appendix A. Hydrographs from observation wells measured monthly—continued.











Appendix B. Average annual output from Soil-Water Program using data for Curtis, McCook, North Platte, and Wallace weather stations for the 1935-1978 time period

[I, infiltration; ET, evapotranspiration; RO, surface runoff; DPI, deep percolation (recharge) from irrigated lands; CIR, consumptive irrigation requirements; DPD, deep percolation (recharge) from drylands; STD, water shortage of drylands]

Soil group	Land use	I	ET	RO	DPI	CIR	DPD	STD
		(inches)						
		Curtis (precipitation, 20.1 inches per year)						
Holdrege-Hall, Kuma-	Row crop	19.1	31.2	1.0	1.1	12.7	0.61	12.6
Keith-Goshen, and	Alfalfa	19.1	38.5	1.0	0.12	17.7	0.12	19.5
Rosebud-Alliance-Kuma	Small grain	19.1	23.2	1.0	2.5	5.9	1.4	5.5
Associations	Pasture	20.1	31.3	0.0	1.2	10.8	0.65	11.8
	Fallow	19.1	23.0	1.0	2.0	5.2	1.0	4.9
Colby-Ulysses	Row crop	18.3	31.2	1.8	1.3	13.2	0.95	13.8
and Coly-Uly	Alfalfa	18.3	38.5	1.8	0.20	17.5	0.20	20.4
Associations	Small grain	18.3	23.2	1.8	2.4	6.3	1.5	6.4
	Pasture	19.1	31.3	1.0	1.0	11.1	0.61	12.8
	Fallow	18.3	23.0	1.8	2.0	5.8	1.1	5.8
Hobbs-Hord-Cozad	Row crop	19.2	31.2	0.90	1.7	12.8	1.2	5.2
Association	Alfalfa	19.2	38.5	0.90	0.87	17.0	0.29	19.5
	Small grain	19.2	23.2	0.90	3.0	6.0	2.0	6.0
	Pasture	20.1	31.3	0.0	1.5	10.7	0.98	12.2
	Fallow	19.2	23.0	0.90	2.5	5.4	1.6	5.2
Jayem Sarben and	Row crop	19.5	31.2	0.60	2.5	12.9	2.1	13.7
Vetal-Hersh	Alfalfa	20.1	38.5	0.0	0.35	15.4	0.23	18.6
Associations	Small grain	20.1	23.2	0.0	4.0	5.8	3.1	6.2
	Pasture	20.1	31.3	0.0	1.9	10.6	1.4	12.6
	Fallow	19.5	23.0	0.60	3.2	5.6	2.3	5.8
Bankard-Las-Glenberg	Row crop	19.2	31.2	0.90	1.8	12.8	1.4	13.2
and McCook-Munjor-	Alfalfa	19.2	38.5	0.90	0.31	16.8	0.29	19.5
Inavale Associations	Small grain	19.2	23.2	0.90	3.1	6.1	2.0	6.1
	Pasture	20.1	31.3	0.0	1.6	10.7	1.1	12.2
	Fallow	19.2	23.0	0.90	2.6	5.4	1.7	5.4
Lawet-Wann-	Row crop	20.1	31.2	0.0	2.7	12.5	2.3	13.3
Lex Association	Alfalfa	20.1	38.5	0.0	0.35	15.4	0.23	
	Small grain	20.1	23.2	0.0	4.0	5.8	3.1	6.2
	Pasture	20.1	31.3	0.0	1.9	10.6	1.4	12.6
	Fallow	20.1	23.0	0.0	3.5	5.3	2.6	5.4
		McCook (precipitation 20.2 inches per year)						
Holdrege-Hall,	Row crop	19.3	32.3	0.90	0.98	13.5	0.47	13.4
Kuma-Keith-Goshen,	Alfalfa	19.3	40.0	0.90	0.09	18.7	0.09	20.7
and Rosebud-Alliance-	Small grain	19.3	24.2	0.90	2.2	6.4	2.2	6.2
Kuma Associations	Pasture	20.2	32.6	0.0	1.0	11.7	0.45	12.8
	Fallow	19.3	23.9	0.90	2.0	5.9	1.0	5.6
Colby-Ulysses and	Row crop	18.6	32.3	1.6	1.2	14.0	0.82	14.5
Coly-Uly Associations	Alfalfa	18.6	40.0	1.6	0.20	18.4	0.20	21.6
	Small grain	18.6	24.2	1.6	2.3	6.6	1.4	7.1
	Pasture	19.3	32.6	0.90	1.0	11.9	0.66	13.9
	Fallow	18.6	23.9	1.6	1.7	6.4	1.3	6.6
Hobbs-Hord-Cozad	Row crop	19.5	19.5	0.70	1.5	13.5	1.0	13.8
Association	Alfalfa	19.5	40.0	0.70	0.28	17.9	0.27	20.8
	Small grain	19.5	24.2	0.70	2.8	6.4	1.8	6.6
	Pasture	20.2	32.6	0.0	1.3	11.6	0.79	13.2
	Fallow	19.5	23.9	0.70	2.5	6.0	1.6	6.0

Appendix B. Average annual output from Soil-Water Program using data for Curtis, McCook, North Platte, and Wallace weather stations for the 1935-1978 time period—Continued

Soil group	Land use	I	ET	RO	DPI	CIR	DPD	STD
		(inches)						
		McCook—Continued						
Bankard-Las-Glenberg and McCook-Munjor-Inavale Associations	Row crop	19.5	32.3	0.70	1.6	13.5	1.2	14.0
	Alfalfa	19.5	40.0	0.70	0.30	17.7	0.28	20.8
	Small grain	19.5	24.2	0.70	2.9	6.4	1.9	6.7
	Pasture	20.2	32.6	0.0	1.4	11.5	0.89	13.3
	Fallow	19.5	23.9	0.70	2.6	6.0	1.7	6.1
		North Platte (precipitation, 19.0 inches per year)						
Holdrege-Hall, Kuma-Keith-Goshen, and Rosebud-Alliance-Kuma Associations	Row crop	18.2	28.7	0.80	1.2	11.5	0.59	11.0
	Alfalfa	18.2	35.5	0.80	0.09	16.2	0.09	17.3
	Small grain	18.2	21.4	0.80	2.5	5.1	1.4	4.5
	Pasture	19.0	28.8	0.0	1.2	10.0	0.61	10.3
	Fallow	18.2	21.1	0.80	2.3	4.7	1.2	4.0
Colby-Ulysses and Coly-Uly Associations	Row crop	17.5	28.7	1.5	1.4	12.0	0.91	12.1
	Alfalfa	17.5	35.5	1.5	0.17	16.1	0.17	18.1
	Small grain	17.5	21.4	1.5	2.5	5.5	1.5	5.3
	Pasture	18.2	28.8	0.79	1.1	10.2	0.59	11.1
	Fallow	17.5	21.1	1.5	2.3	5.2	1.3	4.9
Hobbs-Hord-Cozad Association	Row crop	18.4	28.7	0.60	1.8	11.6	1.2	11.5
	Alfalfa	18.4	35.5	0.60	0.26	15.6	0.22	17.3
	Small grain	18.4	21.4	0.60	3.0	5.3	1.9	4.9
	Pasture	19.0	28.8	0.0	1.5	9.9	0.90	10.7
	Fallow	18.4	21.1	0.60	2.7	4.9	1.7	4.4
Jayem-Sarben and Vetal-Hersh Associations	Row crop	18.6	28.7	0.40	2.5	11.8	2.0	12.2
	Alfalfa	19.0	35.5	0.0	0.43	14.4	0.18	16.6
	Small grain	19.0	21.4	0.0	4.0	5.3	3.0	5.4
	Pasture	19.0	28.8	0.0	1.8	9.8	1.3	11.1
	Fallow	18.6	21.1	0.40	2.4	5.0	2.4	5.0
Valentine and Valent-Tassel Associations	Row crop	19.0	28.7	0.0	4.1	12.3	3.8	13.5
	Alfalfa	19.0	35.5	0.0	1.0	13.5	0.83	17.3
	Small grain	19.0	21.4	0.0	4.8	5.5	4.2	6.5
	Pasture	19.0	28.8	0.0	2.7	9.7	2.4	12.1
	Fallow	19.0	21.1	0.0	4.6	5.2	4.0	6.0
Bankard-Las-Glenberg and McCook-Munjor-Inavale Associations	Row crop	18.4	28.7	0.60	1.9	11.6	1.3	11.6
	Alfalfa	18.4	35.5	0.60	0.28	15.5	0.22	17.3
	Small grain	18.4	21.4	0.60	3.1	5.3	2.1	5.0
	Pasture	19.0	28.8	0.0	1.6	9.8	0.98	10.7
	Fallow	18.4	21.1	0.60	2.8	4.9	1.8	4.5
Lawet-Wann-Lex Association	Row crop	19.0	28.7	0.0	2.7	11.6	2.2	11.8
	Alfalfa	19.0	35.5	0.0	0.43	14.4	0.18	16.6
	Small grain	19.0	21.4	0.0	4.0	5.3	3.0	5.4
	Pasture	19.0	28.8	0.0	1.8	9.8	1.3	11.1
	Fallow	19.0	21.1	0.0	3.5	4.8	2.6	4.7
		Wallace (precipitation, 17.9 inches per year)						
Holdrege-Hall, Kuma-Keith-Goshen, and Rosebud-Alliance-Kuma Associations	Row crop	17.4	31.2	0.50	0.58	13.8	0.24	14.0
	Alfalfa	17.4	38.5	0.50	0.06	19.2	0.06	21.2
	Small grain	17.4	23.2	0.50	1.4	6.5	0.60	6.4
	Pasture	17.9	31.3	0.0	0.55	12.2	0.24	13.6
	Fallow	17.4	23.0	0.50	1.2	6.0	0.43	6.0

Appendix B. Average annual output from Soil-Water Program using data for Curtis, McCook, North Platte, and Wallace weather stations for the 1935-1978 time period—Continued

Soil group	Land use	I	ET	RO	DPI	CIR	DPD	STD
		(inches)						
				Wallace—Continued				
Colby-Ulysses and Coly-Uly Associations	Row crop	16.8	31.2	1.1	0.7	14.1	0.44	14.8
	Alfalfa	16.8	38.5	1.1	0.13	21.8	0.13	21.8
	Small grain	16.8	23.2	1.1	1.4	6.6	0.78	7.2
	Pasture	17.4	31.3	0.50	0.60	12.1	0.26	14.2
	Fallow	16.8	23.0	1.1	1.3	6.4	0.58	6.7
Jayem-Sarben and Vetal-Hersh Associations	Row crop	17.6	31.2	0.30	1.5	13.7	1.1	14.6
	Alfalfa	17.9	38.5	0.0	0.21	17.0	0.05	20.6
	Small grain	17.9	23.2	0.0	2.4	6.2	1.7	7.0
	Pasture	17.9	31.3	0.0	1.0	11.6	0.71	14.1
	Fallow	17.6	23.0	0.30	2.0	6.1	1.4	6.7
Valentine and Valent-Tassel Associations	Row crop	17.9	31.1	0.0	2.8	14.0	2.7	15.9
	Alfalfa	17.9	38.5	0.0	0.61	15.6	0.44	21.0
	Small grain	17.9	23.2	0.0	3.3	6.2	2.8	8.1
	Pasture	17.9	31.3	0.0	1.8	11.2	1.5	14.9
	Fallow	17.9	23.0	0.0	3.2	6.0	2.7	7.7
Lawet-Wann-Lex Association	Row crop	17.9	31.2	0.0	1.6	13.5	1.2	14.4
	Alfalfa	17.9	38.5	0.0	0.21	17.0	0.05	20.6
	Small grain	17.9	23.2	0.0	2.4	6.3	1.7	7.0
	Pasture	17.9	31.3	0.0	1.0	11.7	0.71	14.1
	Fallow	17.9	23.0	0.0	21.2	6.0	1.5	6.5